Karlsruher Institut für Technologie

Karlsruhe Reports in Informatics 2020,1
Edited by Karlsruhe Institute of Technology,
Faculty of Informatics
ISSN 2190-4782

Ubiquitäre Systeme (Seminar) und Mobile Computing (Proseminar) SS 2019

Mobile und Verteilte Systeme
Ubiquitous Computing
Teil XIX

Herausgeber:
Erik Pescara, Paul Tremper, Jan Formanek,
Michael Hefenbrock, Yiran Huang,
Ployplearn Ravivanpong, Johannes Riesterer,
Long Wang, Ingmar Wolff, Yexu Zhou, Michael Beigl

2020

KIT – University of the State of Baden-Wuerttemberg and National Research Center of the Helmholtz Association

Karlsruhe Institute of Technology

Ubiquitäre Systeme (Seminar) und Mobile Computing (Proseminar) SS 2019

Mobile und Verteilte Systeme Ubiquitous Computing

Teil XIX

Herausgeber

Erik Pescara, Paul Tremper
Jan Formanek, Michael Hefenbrock
Yiran Huang, Ployplearn Ravivanpong
Johannes Riesterer, Long Wang
Ingmar Wolff, Yexu Zhou, Michael Beigl

Karlsruhe Institute of Technology (KIT)
Fakultät für Informatik
Lehrstuhl für Pervasive Computing Systems (PCS) und TECO

Interner Bericht 2020-01

Vorwort

Die Seminarreihe Mobile Computing und Ubiquitäre Systeme existiert seit dem Wintersemester 2013/2014. Seit diesem Semester findet das Proseminar Mobile Computing am Lehrstuhl für Pervasive Computing System statt. Die Arbeiten des Proseminars werden seit dem mit den Arbeiten des zweiten Seminars des Lehrstuhls, dem Seminar Ubiquitäre Systeme, zusammengefasst und gemeinsam veröffentlicht.

Die Seminarreihe Ubiquitäre Systeme hat eine lange Tradition in der Forschungsgruppe TECO. Im Wintersemester 2010/2011 wurde die Gruppe Teil des Lehrstuhls für Pervasive Computing Systems. Seit dem findet das Seminar Ubiquitäre Systeme in jedem Semester statt. Ebenso wird das Proseminar Mobile Computing seit dem Wintersemester 2013/2014 in jedem Semester durchgeführt. Seit dem Wintersemester 2003/2004 werden die Seminararbeiten als KIT-Berichte veröffentlicht. Ziel der gemeinsamen Seminarreihe ist die Aufarbeitung und Diskussion aktueller Forschungsfragen in den Bereichen Mobile und Ubiquitous Computing.

Dieser Seminarband fasst die Arbeiten der Seminare des Sommersemesters 2019 zusammen. Wir danken den Studierenden für ihren besonderen Einsatz, sowohl während des Seminars als auch bei der Fertigstellung dieses Bandes.

Karlsruhe, den 01. Oktober 2019

Erik Pescara
Paul Tremper
Jan Formanek
Michael Hefenbrock
Yiran Huang
Ployplearn Ravivanpong
Johannes Riesterer
Long Wang
Ingmar Wolff
Yexu Zhou
Michael Beigl

Contents

Hot Topics in Intelligent User Interfaces

Cem Özcan

Karlsruher Institut für Technologie

Zusammenfassung. Vor allem in den letzten Jahren wurden Computer immer mehr dazu eingesetzt, uns bei der Lösung komplexer Probleme zu assistieren. Aufgrund der steigenden Komplexität der Aufgaben gewinnt eine effiziente Interaktion zwischen Mensch und Maschine für Nutzer also immer mehr an Bedeutung.
Eine Forschungsrichtung, die dieses Problem untersucht, ist die Forschung im Bereich "Intelligent User Interfaces". In diesem Gebiet konzentriert man sich auf die Entwicklung von intuitiven Benutzerschnittstellen, die die Interaktion mit einem Intelligenten System erleichtern und intuitiver gestalten sollen [16,30].

Die aktuelle Forschung richtet sich dabei hauptsächlich auf die Lösung von Problemen im Gebiet "Information retrieval" durch den Einsatz von "Recommender Systems" (Siehe section 2), die nahtlose Integration von Mobilen und Tragbaren Geräten in den Alltag (siehe section 3) und die Bewältigung komplexer Aufgaben durch den Einsatz multimodaler Interaktion (Siehe section 4).
Im Folgenden werden Paper aus der Konferenz "ACM Intelligent User Interfaces" [2] vorgestellt, die repräsentativ für die aktuelle Forschung in diesem Bereich sind.

Schlüsselwörter: Intelligent User Interfaces, Recommender Systems, Explainable Artificial Intelligence, Ubiquitous Computing, Multimodal Interfaces, Human-Centered Computing, Human-Computer-Interaction

1 Einleitung

Als "Intelligent User Interface" werden Schnittstellen zur Kommunikation zwischen Mensch und Maschine bezeichnet, die Aspekte der künstlichen Intelligenz verwenden, um sich dem Nutzer anzupassen. Diese Adaption der Schnittstelle an den Nutzer wird, je nach Beschaffenheit und Einsatzgebiet der Schnittstelle, unterschiedlich umgesetzt und hat demzufolge auch unterschiedliche Auswirkungen auf die Wahrnehmung des Nutzers vom System:

Recommender Systems lösen durch personalisierte Empfehlungen das Problem der Informationsüberflutung und ermöglichen dem Nutzer eine effizientere Kommunikation mit dem System. Im Forschungsfeld Ubiquitous Computing werden Möglichkeiten zur Integration von mobilen und tragbaren Geräten in den menschlichen Alltag untersucht, um alltägliche Probleme des Nutzers zu

2 Cem Özcan

lösen und die Interaktion mit Geräten so natürlich und intuitiv wie möglich zu gestalten. Multimodale Interfaces werden verwendet, um die Mensch-Maschine-Interaktion der zwischenmenschlichen Interaktion anzunähern und dem Nutzer somit zu erlauben, komplexe Aufgaben effizienter zu lösen.

Ziel dieser Arbeit ist es, die genannten Einsatzgebiete intelligenter Benutzerschnittstellen, unter Verwendung relevanter Paper der Konferenz "ACM Intelligent User Interfaces", vorzustellen.

2 Recommender Systems

2.1 Grundlagen

Recommender Systems sind vor allem im Zeitalter der Digitalisierung effektive Dienste, die die Mensch-Maschine-Interaktion erleichtern sollen. Durch Analyse des Nutzerverhaltens versuchen Recommender Systems vorherzusehen, welche Inhalte (im Folgenden auch Items genannt) für den Nutzer interessant sein könnten, um diese dann dem Nutzer zu empfehlen. Das trägt zu einer verbesserten Wahrnehmung vom System von Seiten des Nutzers bei und verbessert so auch die User Experience [6,12,17] .
Das Filtern von irrelevanten Informationen erwies sich, vor allem in den letzten Jahren, als effektiver Ausweg aus der Informationsüberflutung [24,29] und gewann für Nutzer zunehmend an Bedeutung. Diese haben durch den Einsatz von Recommender Systems Zugang zu mehr relevanten Informationen, die bei einer Recherche ohne Hilfe eines solchen Systems, teilweise in der Masse untergegangen wären. Wie in [13] beschrieben kann das Auslassen relevanter Informationen beispielsweise im Gesundheitswesen fatale Folgen nach sich ziehen.
Auch für Unternehmen, die ihre Inhalte im Internet anbieten, spielen Recommender Systems eine wichtige Rolle. Gesammelte Nutzerdaten werden dazu eingesetzt, Massenwerbung nach und nach durch personalisierte Werbung und Produktempfehlungen zu ersetzen, was sich auch im Konsumverhalten der Nutzer bemerkbar macht:
Nach eigenen Angaben haben Netflix und YouTube je 75 und 70 Prozent ihrer Ansichten und Amazon 35 Prozent ihrer Verkäufe ihrem Recommender System zu verdanken [15,32].
Die Genauigkeit der Empfehlungen sind demnach von großer Bedeutung sowohl für die Nutzer als auch für die Anbieter des Systems.
Für die Forschung in diesem Gebiet ergibt sich daher die Herausforderung, das Empfehlen und Filtern von Inhalten durch Personalisierung, zusätzlicher Parametrisierung und Kontextualisierung so präzise wie möglich zu gestalten, ohne dabei die User Experience und Benutzbarkeit des Systems zu komprimieren.
Im Folgenden werden verschiedene Klassen von Recommender Systems und zum Thema relevante Paper vorgestellt, die Ansätze zur Verbesserung der Empfehlungen untersuchen.

Hot Topics in Intelligent User Interfaces 3

2.2 Content-based filtering

Allgemein
Inhaltsbasiertes Filtern ist eines der am häufigsten verwendeten Ansätze bei der Implementierung von Recommender Systems. Grundlegende Informationen, die dem System bekannt sein müssen, sind frühere Itembewertungen der Nutzers und möglichst viele Attribute, die einen Item so präzise wie möglich beschreiben. Basierend auf diesen Daten werden Items kategorisiert und Nutzerprofile erstellt [29].
Folgende Voraussetzungen müssen erfüllt sein, damit ein Item I einem Nutzer U empfohlen wird:

- I wurde noch nicht von Nutzer U bewertet
- I ist ähnlich zu anderen Items, die U in der Vergangenheit positiv bewertet hat

Häufig werden Item- und Nutzerprofile als Term Frequency-Inverse Document Frequency-Vektoren (TF-IDF-Vektoren) dargestellt und die Ähnlichkeit zweier Items mithilfe von Korrelationskoeffizienten oder Abstandsfunktionen berechnet [26,29].

User Experience
Eines der Vorteile inhaltsbasierter Recommender Systems ist die Transparenz und die Möglichkeit für den Nutzer, Empfehlungen nachzuvollziehen. Der Grund, weshalb die Nachvollziehbarkeit von Empfehlungen so wichtig ist, ist, dass sie sich auf die Wahrnehmung auswirkt, die der Nutzer vom System hat [12].
In [12] wurde, mithilfe einer Bilddatenbank, ein Recommender System für Gemälde implementiert. Anschließend wurde in einer Nutzerstudie (N = 121) die Wirkung, die das Erklären von Empfehlungen auf die Nutzer hat, untersucht.
Dabei wurden drei verschiedene Interfaces Implementiert, die die Empfehlungen des Systems auf unterschiedliche Art und Weise erklären sollen:

- I_1 Ohne Erklärungen
- I_2 Zeigt dem Nutzer Bilder, die von diesem Positiv bewertet wurden und ähnlich zum empfohlenen Bild sind
- I_3 Zeigt dem Nutzer, welche visuellen Eigenschaften das empfohlene Bild mit von ihm positiv bewerteten Bildern teilt

Diese Interfaces wurden in Kombination mit zwei verschiedenen inhaltsbasierten Empfehlungsalgorithmen, Deep Neuronal Networks (DNN) und Attractiveness Visual Features (AVF), den Nutzern zum Testen bereitgestellt. DNN generiert präzisere Empfehlungen als AVF, dafür ist der Entscheidungsprozess bei AVF transparenter, was eine Kombination aus I_3 und AVF ermöglicht (dies ist mit DNN nicht möglich).
Dominguez et. al. kamen dabei zum Ergebnis, dass die Kombination aus I_2 und Deep Neuronal Networks von den Nutzern die positivsten Bewertungen erhalten

4 Cem Özcan

hat. Die Kombination aus I_3 und Attractiveness Visual Features ist zwar die transparenteste Methode, hat aber relativ unpräzise Empfehlungen im Vergleich zu anderen Kombinationen. Das hat eine schlechtere Wahrnehmung und Bewertung des Systems aus Sicht der Nutzer zufolge.
Aus [12] kann man also Folgern, dass bei der Implementierung eines Recommender Systems Wert auf Transparenz gelegt werden sollte, wenn diese die Qualität der Empfehlungen nicht abschwächt.

2.3 Collaborative filtering

Allgemein
Anders als beim inhaltsbasieten Filtern werden beim kollaborativem Filtern keine Informationen über den Inhalt eines Items im System benötigt. Stattdessen werden, je nach Ansatz, Nutzer- bzw. Itemprofile basierend auf deren Bewertungshistorie erstellt:

User-based approach
Es werden Nutzerprofile basierend auf Bewertungen, die die Nutzer in der Vergangenheit über Items abgegeben haben, erstellt. Typischerweise wird der k-Nearest-Neighbour-Algorithmus eingesetzt, um Nutzerprofile mit ähnlicher Bewertungshistorie zu finden.
Falls hinreichend viele Nutzer, die sich in der Nachbarschaft des Nutzers U befinden, ein Item I positiv bewertet haben, so bekommt Nutzer U eine Empfehlung für Item I [20,29].

Item-based approach
Es werden Itemprofile basierend auf Bewertungen, die die Items von Nutzern erhalten haben, erstellt.
Zwei Items sind genau dann ähnlich, wenn es hinreichend viele Nutzer gibt, die beide Items bewertet haben. Außerdem muss eine Korrelation im Bewertungsverhalten der Nutzer, bezogen auf genannte Items, existieren.
Diese Informationen werden dann dafür verwendet, die Bewertung eines Nutzers für ein Item abzuschätzen [20,21].

Context-specific trust [24]
Mit der Hypothese, dass kollaboratives Filtern hohes Verbesserungspotential besitzt, hat man in [24] und [14] versucht, mit Modifikationen am kollaborativen Filtern auf bessere Empfehlungen zu kommen.
Die grundlegende Idee des Ansatzes in [24] ist dabei, den Kontext bei der Wahl der Nachbarschaft eines Nutzers zu berücksichtigen. Dazu werden die in [4] eingeführten Definitionen für “Trust“ (Vertrauenswürdigkeit) modelliert und bei der Wahl ähnlicher Profile als zusätzlicher Parameter berücksichtigt:

Hot Topics in Intelligent User Interfaces 5

Profile-Level trust
Die Vertrauenswürdigkeit eines Nutzers U ist abhängig davon, wie präzise die Empfehlungen sind, die andere Nutzer, aufgrund ihrer Ähnlichkeit zu U, erhalten haben.

Item-Level trust
Sei I ein von Nutzer U bewertetes Item. Die Vertrauenswürdigkeit von U im Bezug auf I ist abhängig davon, ob I häufig erfolgreich anderen Nutzern empfohlen wurde, weil diese ähnlich zu U sind.

O'Donovan et. al. haben verschiedene kollaborative Filteralgorithmen mit ihren Modellen erweitert und die Qualität der Empfehlungen miteinander verglichen. Zur Evaluierung der Algorithmen wurde ein Datensatz mit 950 Profilen mit je durchschnittlich 105 Filmbewertungen verwendet.
Die Ergebnisse waren recht Eindeutig: Jeder Algorithmus, der um den zusätzlichen Parameter "Trust" erweitert wurde, hat bessere Empfehlungsergebnisse geliefert, als der unmodifizierte Algorithmus. Die modifizierten Algorithmen waren zwischen 3 und 22 % weniger Fehleranfällig in ihren Empfehlungen, als der unmodifizierte Algorithmus.

2.4 Vergleich beider Ansätze

Inhaltsbasiertes Filtern
Zum Einen ist es nicht notwendig, Persönliche Informationen über die Nutzer zu halten und zum Anderen löst die Kategorisierung der Items das sogenannte "New-Item-Problem" [5,29]. Beim inhaltsbasierten Filtern können also, anders als beim kollaborativem Filtern, auch neue Produkte empfohlen werden, ohne zuvor eine Bewertung zu erhalten. Des Weiteren ist es für Nutzer einfacher nachzuvollziehen, weshalb sie bestimmte Empfehlungen bekommen, was sich positiv auf die User Experience auswirkt (siehe section 2.2) [12] .

Kollaboratives Filtern
Das Hauptproblem inhaltsbasierten Filterns ist der, dass Nutzer nur Empfehlungen erhalten, die sich in dieselben Kategorien einordnen lassen, wie die bereits vom Nutzer bewerteten Items. Durch kollaboratives Filtern können Nutzer auch Empfehlungen aus Kategorien bekommen, die ihnen noch unbekannt waren.
Ein Problem des kollaborativen Filterns ist das sogenannte "Cold-Start-Problem". Neue Nutzer haben keine Bewertungshistorie, weswegen das System ihnen keine Items empfehlen kann.

2.5 Hybrid Recommender Systems

Um von den Vorteilen mehrerer verschiedener Empfehlungsalgorithmen zu profitieren werden häufig "Hybrid Recommender Systems" (hybride Empfehlungsdienste) verwendet. Dies sorgt in der Regel für präzisere Empfehlungen als traditionelles kollaboratives oder inhaltsbasiertes Filtern [5].

6 Cem Özcan

In [18] wurde beispielsweise ein Hybrid Recommender System mit traditionellem kollaborativem Filtern verglichen. Nicht nur waren die Empfehlungen des Hybrid Recommender Systems akkurater, es war außerdem dank inhaltsbasierter Aspekte möglich, Empfehlungen wie in [12] zu Begründen.

Personalized Explanations [18]
Wie auch schon in [12] (siehe section 2.2) wurde in [18] versucht, die Empfehlungen eines Recommender Systems mithilfe unterschiedlicher Methoden zu erklären.
Kouki et. al. haben dafür ein Hybrid Recommender System implementiert, das sieben verschiedene Arten von Erklärungen für die Empfehlungen anbietet und diese in verschiedenen Formaten (visuell oder textuell) darstellt.
Die verschiedenen Erklärungsansätze lassen sich dabei in zwei Kategorien einordnen. Inhaltsbasierte Erklärungen, die Empfehlungen basierend auf deren Inhalt begründen und nutzerbasierte Erklärungen, die Empfehlungen basierend auf der Präferenz ähnlicher Nutzer begründen.
Ziel der Studie [18] war es, durch Variation der Anzahl verschiedener Erklärungen für eine Empfehlung, herauszufinden, welchen Einfluss diese auf die Nutzer haben.
Zur Beantwortung dieser Fragen, wurde das Recommender System mithilfe einer Nutzerstudie (N = 198) evaluiert. Basierend auf einem Datensatz der Musikplattform Last.fm wurden diesen Nutzern Musikinterpreten vorgeschlagen. Die Vorschläge wurden wie schon in [12] von Begründungen begleitet, die dem Nutzer helfen sollen, die Empfehlungen zu verstehen.
Kouki et. al. haben nach einer Befragung genannter Nutzer herausgefunden, dass:

1. Nutzer inhaltsbasierte Erklärungen überzeugender als nutzerbasierte Erklärungen fanden
2. Nutzer im Durchschnitt drei bis vier verschiedene Erklärungsansätze für ihre Empfehlungen bevorzugen
3. Nutzer die textuelle Darstellung der Erklärungen der visuellen Darstellung vorziehen

Ein weiteres interessantes Ergebnis der Studie in [18] war, dass die Genauigkeit des Empfehlungsalgorithmus nicht zu Zwecken der Erklärbarkeit abgeschwächt werden sollte. Auf ein ähnliches Ergebnis sind auch Dominguez et. al. in [12] gekommen (siehe section 2.2).

2.6 Ausblick

Recommender Systems sind schon seit einigen Jahren fester Bestandteil des elektronischen Handels und sind für eine Pluralität der Einnahmen vieler E-Commerce-Unternehmen verantwortlich. Durch den weitläufigen Einsatz von Recommender Systems richtet sich die Forschung in diesem Bereich also nicht auf die Exploration neuer Einsatzmöglichkeiten, sondern zielt vielmehr auf die

Hot Topics in Intelligent User Interfaces 7

Verbesserung der Präzision von Empfehlungen ab. Um die Qualität von Empfehlungen zu verbessern, werden typischerweise zusätzliche Kontextinformationen in den Empfehlungsprozess hinzugezogen. Damit das Recommender System allerdings Skalierbar bleibt, muss der zusätzliche Rechenaufwand des Empfehlungsprozesses minimal gehalten werden.
Ein anderer Ansatz ist die Kombination von Recommender Systems mit Explainable Artificial Intelligence. Das Ziel ist es, durch Erklärungen, den Empfehlungsprozess so transparent wie möglich zu gestalten. Diese Erklärungen tragen zwar nicht zur Verbesserung der Empfehlungen bei, scheinen aber ein wichtiger Faktor bei der Wahrnehmung des Nutzers vom System zu sein.

3 Ubiquitous Computing

3.1 Grundlagen

Der Begriff "Ubiquitous Computing" beschreibt die Eingliederung von Computern in den menschlichen Alltag und wurde bereits 1991 von Mark Weiser (1952-1999) verwendet und geprägt [37]. Das Ziel des "Ubiquitous Computing" ist es, das alltägliche Leben des Menschen mithilfe von intelligenten Geräten, die aus dem Hintergrund heraus agieren, zu erleichtern. Weisers Vorstellung des 21. Jahrhunderts hat sich als richtig herausgestellt: Heutzutage suchen Nutzer die Interaktion mit Computern nicht länger aktiv auf, vielmehr ist die Mensch-Maschine-Interaktion allgegenwärtig ohne dabei im Vordergrund unseres Lebens zu sein.
Die Veröffentlichungen der Konferenz "Intelligent User Interfaces" beschäftigen sich vor allem mit den Themen "Mobile Computing" und "Wearable Computing", da Smartphones und andere mobile bzw. tragbare Geräte zunehmend an Bedeutung in unserem Alltag gewinnen.

3.2 Wearable Computing

„Wearable devices" sind am Körper getragene Geräte, die den Nutzer im Alltag unterstützen sollen, ohne dabei von diesem als störend empfunden zu werden. Ein typisches Beispiel für Wearables aus dem kommerziellen Bereich sind Fitnessarmbänder:
Durch die Positionierung am Handgelenk des Nutzers können diese den Nutzer durch das Messen der Vitalfunktionen und Körperbewegung (Pulsmesser und Schrittzähler) beim Sport unterstützen, ohne dessen Bewegungen einzuschränken.
In der Forschung hingegen, werden Wearables vor allem mit Blick auf die Verbesserung der Mensch-Maschine-Interaktion eingesetzt.

8 Cem Özcan

3.3 Assistive Intelligent User Interfaces

Eine Vielzahl der Arbeiten, die auf der Konferenz vorgestellt werden, richtet sich auf Unterstützungstechnologien zur Hilfe von Menschen mit kognitiven Beeinträchtigungen [10,23]. Speziell Wearables beispielsweise werden hauptsächlich dafür eingesetzt, um die Kommunikation und Interaktion zwischen seh- bzw. hörgeschädigten Personen mit Personen ohne jeweilige Einschränkungen zu erleichtern [8,27,28,38].
Paudyal et. al. haben sich sowohl in [27] als auch in [28] mit dem Einsatz von Wearables zur Erkennung von Gesten in der Gebärdensprache beschäftigt:

SCEPTRE [27]
Mit dem Ziel, die Kommunikation zwischen Personen zu erleichtern, von denen nur eine die "American Sign Language" (ASL) beherrscht, haben Paudyal et. al. die Applikation SCEPTRE entwickelt, die ASL-Gesten erkennen und übersetzen soll. Zur Erkennung von Gesten werden Myo-Armbänder [19] verwendet, die der Nutzer während der zweistufigen Interaktion mit dem System tragen muss:

Training : Die Gestenerkennung des Systems ist abhängig vom Nutzer. Aus diesem Grund ist es für den Nutzer erforderlich, dem System zu Beginn der Interaktion Gesten beizubringen. Dafür wählt der Nutzer über die App eine ASL-Geste und führt diese drei mal aus.
Durch die Sensoren im Myo-Armband (Gyroskop, Beschleunigungssensor, Elektromyographiesensor) hat das System nun Sensordaten zur ausgewählten ASL-Geste. Diese verwendet das System, um eine Vorlage (Template) von der neu erlernten ASL-Geste zu erstellen.

Gestenerkennung : Zur Erkennung von Gesten wird "Template matching" verwendet. Die Inputdaten einer Geste werden dafür mittels Dynamic Time Wrapping mit den im *Training* erstellten Templates verglichen. Die ASL-Geste, deren Template dem Input am ähnlichsten ist, wird vom System vorgeschlagen.

Anschließend wurde die Gestenerkennung in einer Nutzerstudie auf Genauigkeit, Reaktionszeit und Benutzbarkeit geprüft:

Evaluation : Dem System wurden 20 Wörter aus dem ASL beigebracht. Im Fall, dass derselbe Nutzer das System trainiert und getestet hat, hatte das System, unter Verwendung aller Sensoren, in eine Genauigkeit von 97.72%. Im Fall, dass das Testen und Trainieren des Systems von verschiedenen Nutzern übernommen wurden, waren die Ergebnisse deutlich schlechter. Dies wurde damit begründet, dass vor allem die Messwerte des Elektromyographiesensors sehr stark vom Nutzer abhängig sind.

Hot Topics in Intelligent User Interfaces 9

Dynamic Feature Selection and Voting (DyFAV) [28]
Um ihre Arbeit in [27] zu erweitern, haben Paudyal et. al. mit DyFAV ein weiteres System zur Gestenerkennung implementiert. Anders als SCEPTRE soll DyFAV allerdings keine ASL-Worte, sondern ASL-Buchstaben erkennen. Wie auch schon in SCEPTRE wurden Myo-Armbänder für den Input und die Sensordaten verwendet.

Initialisierung : Aufgrund der Beschränktheit des ASL-Alphabets (26 Buchstaben), ist es für den Nutzer nicht länger erforderlich, das System nach einer Initialisierung weiterhin zu trainieren. Zu Beginn der Interaktion mit DyFAV muss der Nutzer lediglich jeden Buchstaben im ASL-Alphabet fünf mal wiederholen, um die Gestenerkennung vollständig verwenden zu können.

Gestenerkennung : Zur Erkennung von Gesten wird Feature Engineering verwendet. Dafür werden auf Basis der Sensordaten aus der *Initialisierung* verschiedene Features miteinander Verglichen. Für jeden ASL-Buchstaben werden dann die für die Klassifikation Signifikantesten Features ausgewählt und in Abhängigkeit ihrer Signifikanz gewichtet.
Basierend auf diesen Gewichten wird dann versucht, die Input-Gesten in Echtzeit zu klassifizieren.

Evaluation : Im Gegensatz zu ASL-Worten unterscheiden sich ASL-Buchstaben Hauptsächlich in der Positionierung der Finger und erfordern beim Gestikulieren kaum Bewegung im Arm. Das Erkennen von Gesten ist in DyFAV also vielmehr vom Elektromyographiesensor als von den anderen beiden Sensoren abhängig, was die Gestenerkennung zusätzlich erschwert.
Durch die Wahl hinreichend vieler Features, die für die Klassifikation eingesetzt werden, ist das System dennoch sehr präzise:
In einer Nutzerstudie (N = 9) wurden 95.36% der Gesten vom System erkannt.

3.4 Mobile Computing

Durch die steigende Beliebtheit von Smartphones seit 2007 [34] gewann auch die Forschung im Bereich “mobile Computing“ immer mehr an Bedeutung. Heutzutage sind Smartphones in unserem Alltag allgegenwärtig und ersetzen für viele Nutzer stationäre Geräte wie Desktop PCs.
Die folgenden Paper richten sich danach, den Entwicklungs- und Fehlerbehebungsprozess mobiler Software, unter Berücksichtigung von Nutzerinteressen, so effizient wie möglich zu gestalten.

User feedback
Eine effektive Methode, um die Lebensdauer eines Softwareprodukts zu erhöhen, ist die Software auf Basis von Nutzerrezensionen zu Aktualisieren. App-Rezensionen werden jedoch häufig mit Kommentaren umgesetzt, was aufgrund der Unabhängigkeit der einzelnen Kommentare unstrukturiert ist.

10 Cem Özcan

Aus diesem Grund ist es sehr schwierig für Entwickler, für die Entwicklung relevantes Feedback aus den Kommentaren zu extrahieren [11].
Zur Lösung dieses Problems haben Su'a et. al. QuickReview entwickelt [35]:
QuickReview ist ein Intelligent User Interface, das das Rezensierten von Apps benutzerfreundlicher gestalten soll und außerdem Entwicklern erlaubt, effizient für die Entwicklung relevante Informationen aus diesen Rezensionen zu gewinnen:

Interaktion : QuickReview stellt dem Nutzer eine Liste von Features der App, die dieser bewerten möchte, zur Verfügung. Der Nutzer kann dann ein Feature auswählen, das es kritisieren möchte, und bekommt dann eine Liste von Issues vorgeschlagen, die abhängig vom ausgewählten Feature ist. Um eine App zu rezensieren, muss der Nutzer also lediglich ein fehlerhaftes Feature auswählen und aus einer Liste von Issues diejenigen auswählen, die den Fehler am besten beschreiben.
Um diese Adaptivität zu gewährleisten, werden vorhandene Kommentare über die zu Bewertende App, mittels Natural Language Processing nach Häufig vorkommenden Feature, Issue Paaren untersucht.

Feedback : Durch Rezensionen nach diesem Schema kann QuickReview eine nach Häufigkeit sortierte Liste aus Feature, Issue Paaren präsentieren. Entwickler können diese Liste dann zur Identifizierung und anschließender Behebung von Bugs verwenden.

Evaluation : Zur Evaluation des Systems wurde eine Nutzerbefragung (N = 20) durchgeführt, bei der die Nutzer zunächst die App "MyTracks" nutzen und später unter Verwendung von QuickReviw rezensieren sollten. Anschließend haben die Nutzer die Benutzbarkeit und kognitive Überlastung von QuickReviw bewertet. Als Kontrollinstanz wurde das traditionelle Rezensionssystem von Google Play verwendet, welches auf einfachen Kommentaren basiert.
QuickReview hat zwar in beiden Kategorien besser abgeschnitten als Google Play, diese Unterschiede waren jedoch statistisch nicht signifikant genug, um eine Aussage über die Präferenz der Nutzer zu treffen.
Allerdings ist bei der Durchführung der Studie aufgefallen, dass die Nutzung von QuickReview deutlich weniger Zeit in Anspruch genommen hat, als das Schreiben von Kommentaren auf Google Play. Das führt zu der Vermutung, dass QuickReview aufgrund der Zeitersparnis Nutzer dazu anregen könnte, mehr Rezensionen abzugeben als traditionelle Systeme.
Ein weiterer Vorteil ist offensichtlicherweise die Zeitersparnis für die Entwickler, da QuickReview das Problem der Informationsüberflutung für diese löst.

3.5 Ausblick

Mobile Geräte, wie Smartphones, sind im Vergleich zu tragbaren Geräten bereits allgegenwärtig und in den menschlichen Alltag integriert. Der Fokus der aktuellen Forschung liegt daher viel mehr auf dem Gebiet Wearable Computing:

Hot Topics in Intelligent User Interfaces 11

Die meisten Paper der Konferenz gehen auf spezifische Alltagssituationen ein und versuchen diese durch den Einsatz tragbarer Geräte zu verbessern. In [22] beispielsweise, werden tragbare Geräte an einem Nutzer angebracht, um dessen Stimme, Gestik und Blick während einer Präsentation zu messen und diesem automatisiertes Feedback zu geben.
Weitaus nützlicher ist der Einsatz von tragbaren Geräten aber, wenn es um die Implementierung assistiver Technologien geht. Nichtinvasive tragbare Geräte, wie beispielsweise Armbänder, haben das Potential durch ihre Allgegenwärtigkeit die Lebensqualität von Hörgeschädigten signifikant zu verbessern.
Aufgrund des Nutzens und der bisherigen Befunde ist also anzunehmen, dass assistive Technologien auch in Zukunft Fokus im Bereich Wearable Computing bleiben werden.

4 Multimodal Interfaces

4.1 Grundlagen

Traditionellerweise ist die Mensch-Maschine-Interaktion mit vielen Systemen unimodal, es wird also nur eine Art der Eingabe verwendet, um das System zu steuern. Mittlerweile werden aber neben Tastatur, Maus und Touchscreens auch andere Eingabemöglichkeiten wie Spracherkennung, Gestenerkennung und Eye Tracking immer präziser und beliebter und können für eine Effektivere Kommunikation zwischen Mensch und Maschine eingesetzt werden.[1]
Dieser Fortschritt motiviert dazu, die Mensch-Maschine-Interaktion an zwischenmenschliche Interaktionen anzunähern, indem die Interaktion multimodal gestaltet wird [25,31,36].

multimodale Interfaces kombinieren mehrere Interaktionsmöglichkeiten miteinander und helfen Nutzern somit, komplexe Aufgaben effizienter zu bewältigen [9]. Das System ist somit durch den Einsatz mehrerer Interaktionsmöglichkeiten weniger Fehleranfällig und sorgt durch die erhöhte Präzision in der Erkennung von Nutzereingaben für eine bessere Wahrnehmung des Systems.
Das Ziel multimodaler Interfaces ist es also, die Stärken der einzelnen Modalitäten zu kombinieren, ohne dass die Interaktion mit dem System vom Nutzer als kontraintuitiv wahrgenommen wird.

4.2 Natural Language Interfaces

Ein großes Problem bei der Bedienung von Geräten mittels Sprachsteuerung ist, dass Nutzer häufig nicht wissen, wie genau sie Befehle formulieren müssen, damit sie das System versteht. Dies führt häufig zu Kommunikationsfehlern zwischen Nutzer und Gerät und hat daher die Auswirkung, dass Nutzer eine negative Wahrnehmung von der Sprachsteuerung oder sogar vom gesamten System haben.
Um dem entgegenzuwirken, wird in [33] versucht, Sprachbefehle in die Benutzeroberfläche zu integrieren, um somit Nutzer mit der sprachlichen Interaktion

12 Cem Özcan

mit dem System vertraut zu machen und Kommunikationsfehler zu vermeiden. Srinivasan et. al. implementierten dafür ein multimodales Interface für ein einfaches Programm zur Bildbearbeitung. Nutzer sollen dazu in der Lage sein, sowohl mittels Touchscreen, als auch mithilfe von Sprachbefehlen mit dem System zu interagieren.
In der Umsetzung wurden drei verschiedene Interfaces implementiert und miteinander verglichen:

- *Exhaustive* : Der Nutzer kann ein Fenster aufrufen, auf dem alle möglichen Sprachbefehle aufgelistet sind. Um die kognitive Belastung auf den Nutzer so gering wie möglich zu halten, werden nur Befehle eingeblendet, die in der jeweiligen Situation verwendbar sind.

- *Adaptive* : Es werden Situationsabhängige Sprachbefehle im Bezug auf einzelne UI-Objekte empfohlen. Der Nutzer kann durch einfaches Zeigen auf ein UI-Objekt eine Liste von Sprachbefehlen auftauchen lassen. Das System versucht auf Basis vergangener Befehle vorherzusehen, welche Befehle der Nutzer als nächstes verwenden wollen könnte. Diese werden dann in der Liste angezeigt.

- *Embedded* : In dem Teil der Benutzeroberfläche, mit dem der Nutzer interagiert, werden neben den UI-Elementen auch die zugehörigen Sprachbefehle angezeigt.

Zur Evaluation des Systems wurden die unterschiedlichen Interfaces in einer Nutzerstudie (N = 16) getestet und miteinander verglichen. Um die Testbedingungen so realistisch wie möglich zu gestalten, wurde die Plattform UserTesting [3] verwendet. Die Teilnehmer haben kein ausführliches Training mit dem System erhalten und haben es auf ihren eigenen Geräten getestet.
Am ende der Studie wurde festgestellt, dass die Interfaces *Adaptive* und *Embedded* deutlich mehr zur sprachlichen Interaktion mit dem System angeregt haben, als das Interface *Exhaustive*.
Des Weiteren hatte die Empfehlung von Befehlen hauptsächlich zwei Auswirkungen auf die Nutzer: Zum einen hatten die Empfehlungen zur Folge, dass nur ein recht kleiner Anteil aller Spracherkennungsfehler (18%) daran lagen, dass Nutzer sich falsch ausgedrückt haben.
Zum anderen haben sich Nutzer dank der Empfehlungen dazu angeregt gefühlt, die Spracherkennungsfunktion zu nutzen und hatten trotz hoher Fehlerquote in der Spracherkennung (44%) eine positive Wahrnehmung vom Spracherkennungsaspekt des Systems.

4.3 Touch gestures

Dank ihrer Kompaktheit sind Smartphones und vor allem Tablets für das Lesen von Dokumenten wie geschaffen. Die Suche nach relevanten Dokumenten

Hot Topics in Intelligent User Interfaces 13

erfordert jedoch häufig die Eingabe von Schlüsselbegriffen von Seiten des Nutzers. Diese Methode mag zwar effektiv sein, wurde jedoch speziell unter der Annahme entwickelt, dass der Nutzer eine Tastatur zur Eingabe benutzt.
Mit der Hypothese, dass es eine für Smartphone- und Tabletnutzer Benutzerfreundlichere Methode zur Suche relevanter Dokumente gibt, haben Beltran et. al. *BINGO* [7] entwickelt:

BINGO soll dem Nutzer die Suche nach relevanten Dokumenten mithilfe von Wischgesten zu ermöglichen. Nutzer Bewerten dafür Dokumente die ihnen vom System empfohlen werden, indem sie es an den rechten Bildschirmrand wischen, falls das Dokument relevant für ihre Recherche war, und an den linken, falls nicht.
Um dem Nutzer genaueres Feedback zu ermöglichen, generiert das System fünf Schlüsselbegriffe ("Reason bins") aus dem Dokument, die auf beiden Seiten des Displays angezeigt werden. Der Nutzer kann das Dokument dann in eines dieser "Reason bins" wischen, falls der darin enthaltene Schlüsselbegriff besonders (un-)nützlich für seine Recherche ist. Diese zusätzliche Information wird dann bei der Empfehlung von Dokumenten an den Nutzer berücksichtigt.

Umsetzung : Zur technischen Umsetzung wird das TF-IDF-Maß verwendet. Dabei wird die Vorkommenshäufigkeit von Worten in Dokumenten ermittelt, um dem Nutzer relevante Dokumente zu empfehlen und "Reason bins" für diese zu generieren.

Evaluation : *BINGO* wurde in verschiedenen Szenarien und Aspekten mit zwei weiteren Methoden verglichen:
In einer Nutzerstudie (N = 20) sollten Nutzer aus einem Datensatz (je 2.035 bzw. 44.150 Dokumente) möglichst viele Dokumente passend zu einem bestimmten Thema finden und speichern. Die Teilnehmer haben dafür neben BINGO folgende Systeme verwendet:

- Simple Swipes (*SWP*):
  Wie *BINGO* ohne "Reason bins". Nutzer wischen nach rechts, falls sie das Dokument relevant finden, sonst nach links.

- Keyword Specification (*KWD*):
  Nutzer beschreiben das Dokument, indem sie Schlüsselbegriffe selber schreiben und das Dokument anschließend bewerten.

Die Bewertung von Dokumenten mit *SWP* war im Vergleich zur Bewertung mit *KWD* deutlich schneller und Intuitiver, jedoch waren die Dokumentempfehlungen von *KWD* deutlich relevanter für die Nutzer. Es hat sich herausgestellt, dass *BINGO* nicht nur ein Kompromiss zwischen *SWP* und *KWD* ist, sondern sich den Stärken beider Methoden annähert:
Während die Durchschnittliche Zeit zwischen einzelnen Bewertungen in *BINGO* sehr ähnlich zu den Zeiten in *SWP* waren, war die Präzision von *BINGO* (Anzahl gespeicherte Dokumente / Anzahl gelesene Dokumente) sehr ähnlich zu der

14 Cem Özcan

von KWD. Auch in einer anschließenden Nutzerbefragung wurde das von den Nutzern bestätigt.
$BINGO$ sei wie SWP sehr intuitiv ($BINGO$ bewertet mit 7, SWP mit 7.6 von 10), während es wie KWD relevante Dokumente empfiehlt ($BINGO$ bewertet mit 7.5, KWD mit 7.5 von 10).

4.4 Ausblick

Wie auch schon im Bereich Ubiquitous Computing erörtern Paper der Konferenz die Einsatzmöglichkeiten von Multimodal Interfaces. Das liegt hauptsächlich daran, dass multimodale Interaktion mit Geräten zu kompliziert für eine sporadische Nutzung ist und die ungeteilte Aufmerksamkeit des Nutzers erfordert. Der Nachteil darin liegt, dass Nutzer häufig nur eine Modalität zur Eingabe nutzen, und die Anderen einfach ignorieren.
Multimodal Interfaces werden daher zur Bewältigung komplexer Aufgaben eingesetzt, statt Probleme im Alltag zu lösen. Wie bereits in [33] angesprochen, ermöglicht multimodale Interaktion Experten eine effizientere Kommunikation mit dem Gerät und erlaubt es ihnen, mehrere Aufgaben zur selben Zeit zu erledigen. Ein weiteres Beispiel, das repräsentativ für die Forschung in diesem Bereich ist, ist die Arbeit an Head-Up-Displays (HUD). In [9] werden Touchscreens durch HUDs in Kombination mit Eye-Tracking ersetzt, um Piloten die Erfüllung von Aufgaben während des Fliegens zu erleichtern.

5 Gemeinsamkeiten und Unterschiede

Gemeinsamkeiten und Unterschiede zwischen den Papern der Konferenz sind stark vom vorgestellten Thema abhängig. Die Paper zu Recommender Systems beispielsweise, stellen die technische Umsetzung neuer Methoden und Algorithmen vor. Das hat zur Folge, dass die Methoden und Algorithmen einfach unter Verwendung von Datensätzen evaluiert werden können.
In Gebieten wie “Ubiquitous Computing“ und “Multimodal Interfaces“ sind stattdessen Nutzerstudien nötig, da hier in erster Linie verschiedene Einsatzmöglichkeiten untersucht werden.
Die Notwendigkeit von Nutzerstudien ist besonders dann ein Problem, wenn sich die Forschung auf sehr spezifische Szenarien richtet:
Bei der Evaluation assistiver Systeme für hörgeschädigte Personen beispielsweise, ist es schwer, Studienteilnehmer zu finden, die die Gebärdensprache können.

6 Fazit

Ein Großteil der Forschung richtet sich auf die Lösung von Problemen im Bereich “Information Retrieval“ mithilfe von Recommender Systems. Der Grund, weshalb gerade Recommender Systems zentral zur Forschung in diesem Gebiet sind, liegt am weit verbreiteten Einsatz von Recommender Systems im

Hot Topics in Intelligent User Interfaces 15

elektronischen Handel.
Auf der Konferenz vorgestellte Paper beschäftigen sich dabei vor allem mit der Verbesserung der "User Experience" bei der Interaktion mit dem System und kommen häufig zum Entschluss, dass die Genauigkeit und Nachvollziehbarkeit von Empfehlungen für die Wahrnehmung eines Recommender Systems von großer Bedeutung sind.

Anders verhält es sich bei der Forschung im Bereich "Ubiquitous Computing" und "Multimodal Interfaces":
Viele Paper versuchen eine sinnvolle Verwendung für tragbare Geräte und multimodale Interfaces zu finden, indem sie versuchen, diese in verschiedene Situationen zu integrieren. Durch die Allgegenwärtigkeit und intuitive Bedienbarkeit von Smartphones erweist es sich als schwer, Alltagssituationen zu finden, in denen Nutzer tragbare Geräte und multimodale Interaktion einem Smartphone mit Touchscreens vorziehen würden.
Aus diesem Grund konzentriert sich die Forschung auf spezifischere Situationen: Tragbare Geräte werden deshalb zur Präzisierung assistiver Technologien verwendet, während multimodale Interaktion häufiger zur Bewältigung komplexer Aufgaben eingesetzt wird.

Literatur

1. Amazon sold tens of millions of echo devices in 2018. https://www.cnet.com/news/amazon-sold-tens-of-millions-of-echo-devices-in-2018/. Accessed: 2019-06-29.
2. Intelligent user interfaces. https://iui.acm.org/2019/. Accessed: 2019-06-18.
3. Usertesting. https://www.usertesting.com/. Accessed: 2019-06-30.
4. Alfarez Abdul-Rahman and Stephen Hailes. A distributed trust model. In *Proceedings of the 1997 workshop on New security paradigms*, pages 48–60. ACM, 1998.
5. Gediminas Adomavicius and Alexander Tuzhilin. Toward the next generation of recommender systems: A survey of the state-of-the-art and possible extensions. *IEEE Transactions on Knowledge & Data Engineering*, (6):734–749, 2005.
6. Paritosh Bahirat, Yangyang He, Abhilash Menon, and Bart Knijnenburg. A data-driven approach to developing iot privacy-setting interfaces. In *23rd International Conference on Intelligent User Interfaces*, pages 165–176. ACM, 2018.
7. Juan Felipe Beltran, Ziqi Huang, Azza Abouzied, and Arnab Nandi. Don't just swipe left, tell me why: Enhancing gesture-based feedback with reason bins. In *Proceedings of the 22nd International Conference on Intelligent User Interfaces*, pages 469–480. ACM, 2017.
8. Syed Masum Billah, Vikas Ashok, and IV Ramakrishnan. Write-it-yourself with the aid of smartwatches: A wizard-of-oz experiment with blind people. In *23rd International Conference on Intelligent User Interfaces*, pages 427–431. ACM, 2018.
9. Pradipta Biswas and Jeevithashree DV. Eye gaze controlled mfd for military aviation. In *23rd International Conference on Intelligent User Interfaces*, pages 79–89. ACM, 2018.
10. Cong Chen, Ajay Chander, and Kanji Uchino. Guided play: digital sensing and coaching for stereotypical play behavior in children with autism. In *Proceedings of*

16 Cem Özcan

the 24th International Conference on Intelligent User Interfaces, pages 208–217. ACM, 2019.
11. Ning Chen, Jialiu Lin, Steven CH Hoi, Xiaokui Xiao, and Boshen Zhang. Arminer: mining informative reviews for developers from mobile app marketplace. In *Proceedings of the 36th International Conference on Software Engineering*, pages 767–778. ACM, 2014.
12. Vicente Dominguez, Pablo Messina, Ivania Donoso-Guzmán, and Denis Parra. The effect of explanations and algorithmic accuracy on visual recommender systems of artistic images. In *Proceedings of the 24th International Conference on Intelligent User Interfaces*, pages 408–416. ACM, 2019.
13. Ivania Donoso-Guzmán and Denis Parra. An interactive relevance feedback interface for evidence-based health care. In *23rd International Conference on Intelligent User Interfaces*, pages 103–114. ACM, 2018.
14. Lukas Eberhard, Simon Walk, Lisa Posch, and Denis Helic. Evaluating narrative-driven movie recommendations on reddit. In *Proceedings of the 24th International Conference on Intelligent User Interfaces*, pages 1–11. ACM, 2019.
15. Ian MacKenzie et. al. How retailers can keep up with consumers. https://www.mckinsey.com/industries/retail/our-insights/how-retailers-can-keep-up-with-consumers. Accessed: 2019-06-18.
16. Kristina Höök. Steps to take before intelligent user interfaces become real. *Interacting with computers*, 12(4):409–426, 2000.
17. Joseph A Konstan and John Riedl. Recommender systems: from algorithms to user experience. *User modeling and user-adapted interaction*, 22(1-2):101–123, 2012.
18. Pigi Kouki, James Schaffer, Jay Pujara, John O'Donovan, and Lise Getoor. Personalized explanations for hybrid recommender systems. In *Proceedings of the 24th International Conference on Intelligent User Interfaces*, pages 379–390. ACM, 2019.
19. Thalmic Labs. Myo gestensteuerungsarmband - schwarz. https://www.robotshop.com/de/de/myo-gestensteuerungsarmband-schwarz.html. Accessed: 2019-06-26.
20. Greg Linden, Brent Smith, and Jeremy York. Amazon. com recommendations: Item-to-item collaborative filtering. *IEEE Internet computing*, (1):76–80, 2003.
21. Gregory D Linden, Jennifer A Jacobi, and Eric A Benson. Collaborative recommendations using item-to-item similarity mappings, July 24 2001. US Patent 6,266,649.
22. Alaeddine Mihoub and Grégoire Lefebvre. Social intelligence modeling using wearable devices. In *Proceedings of the 22Nd International Conference on Intelligent User Interfaces*, IUI '17, pages 331–341, New York, NY, USA, 2017. ACM.
23. Leo Neat, Ren Peng, Siyang Qin, and Roberto Manduchi. Scene text access: a comparison of mobile ocr modalities for blind users. 2019.
24. John O'Donovan and Barry Smyth. Trust in recommender systems. In *Proceedings of the 10th international conference on Intelligent user interfaces*, pages 167–174. ACM, 2005.
25. Sharon Oviatt and Philip Cohen. Perceptual user interfaces: multimodal interfaces that process what comes naturally. *Communications of the ACM*, 43(3):45–53, 2000.
26. Martin Kuhl Max Leonhardt Christoph Schröer Achim Völz Lukas Weinel Christian Wigger Christof Wolke Marius Wybrands Patrick Bruns, Christian Eilts. *Datenstrombasierte Recommender-Systeme*. Carl von Ossietzky Universität Oldenburg.
27. Prajwal Paudyal, Ayan Banerjee, and Sandeep KS Gupta. Sceptre: a pervasive, non-invasive, and programmable gesture recognition technology. In *Proceedings of*

Hot Topics in Intelligent User Interfaces 17

the 21st International Conference on Intelligent User Interfaces, pages 282–293. ACM, 2016.
28. Prajwal Paudyal, Junghyo Lee, Ayan Banerjee, and Sandeep KS Gupta. Dyfav: Dynamic feature selection and voting for real-time recognition of fingerspelled alphabet using wearables. In *Proceedings of the 22nd International Conference on Intelligent User Interfaces*, pages 457–467. ACM, 2017.
29. Francesco Ricci, Lior Rokach, and Bracha Shapira. Introduction to recommender systems handbook. In *Recommender systems handbook*, pages 1–35. Springer, 2011.
30. Edwina L Rissland. Ingredients of intelligent user interfaces. *International Journal of Man-Machine Studies*, 21(4):377–388, 1984.
31. Monica Sebillo, Giuliana Vitiello, and Maria De Marsico. *Multimodal Interfaces*, pages 1838–1843. Springer US, Boston, MA, 2009.
32. Joan E. Solsman. Youtube's ai is the puppet master over most of what you watch. https://www.cnet.com/news/youtube-ces-2018-neal-mohan/. Accessed: 2019-06-18.
33. Arjun Srinivasan, Mira Dontcheva, Eytan Adar, and Seth Walker. Discovering natural language commands in multimodal interfaces. In *Proceedings of the 24th International Conference on Intelligent User Interfaces*, pages 661–672. ACM, 2019.
34. Statista. Endkundenabsatz von smartphones weltweit von 2007 bis 2018. https://de.statista.com/statistik/daten/studie/12856/umfrage/absatz-von-smartphones-weltweit-seit-2007/. Accessed: 2019-06-29.
35. Tavita Su'a, Sherlock A Licorish, Bastin Tony Roy Savarimuthu, and Tobias Langlotz. Quickreview: A novel data-driven mobile user interface for reporting problematic app features. In *Proceedings of the 22nd International Conference on Intelligent User Interfaces*, pages 517–522. ACM, 2017.
36. Alex Waibel, Minh Tue Vo, Paul Duchnowski, and Stefan Manke. Multimodal interfaces. *Artificial Intelligence Review*, 10(3-4):299–319, 1996.
37. Mark Weiser. The computer for the 21 st century. *Scientific american*, 265(3):94–105, 1991.
38. Qian Zhang, Dong Wang, Run Zhao, and Yinggang Yu. Myosign: enabling end-to-end sign language recognition with wearables. In *Proceedings of the 24th International Conference on Intelligent User Interfaces*, pages 650–660. ACM, 2019.

Room Recognition Using Audio Signals

Rudolf Kellner [*ukhwr@student.kit.edu*]

Tutor: Long Wang [*wanglong@teco.edu*]

[1] Karlsruher Institut für Technologie, 76131 Karlsruhe, Germany
info@kit.edu
[2] Technology for Pervasive Computing (TECO), 76131 Karlsruhe, Germany
sekretariat@teco.edu

Abstract. In recent years multiple approaches for room recognition using audio signals have been published. This paper describes and evaluates many of them. The focus thereby is on approaches that do not require additional infrastructure and solely require a handheld device on the client side. The paper categorizes all those systems into either active or passive sound fingerprinting. Some approaches achieve a recognition accuracy of over 90% under optimal conditions. The results show, that active sound fingerprinting outclasses its passive counterpart in all respects. However, using acoustic signals comes with some drawbacks like susceptibility towards background noises or an increasing dataset size.

Keywords: Room recognition, indoor localization, sound fingerprinting.

1 Introduction

Due to the technological progress in recent years, especially regarding the mobile computing sector, new and existing challenges gain in importance. One of them is indoor localization. Localization outdoors with a precision of up to a few centimeters is a long-solved topic. GPS, a navigation system owned by the US government which is available to the public since the 1980s, is the most commonly used service. Despite its flaws, for example a high energy consumption in comparison to other techniques [8], it offers a reliable and precise localization of up to one to five meters in real-time usage. Galileo [9], a European alternative to GPS which is expected to launch in 2020, could be a future alternative.
Indoor localization on the other hand still lags relevant and practicable breakthroughs. However, several approaches to solve this issue have been studied and conducted in past years. Most of them are using smartphones as the source for signal input. This paper categorizes those approaches by two factors.
The first one being which sensors and signal types are used to calculate the position of the device. Some approaches even require additional hardware in form of beacons [7] or access points. Measuring Wi-Fi signals and acoustic data are the most commonly used methods. While using one type of signal or sensor can achieve satisfactory re-

sults, some applications combine multiple signal types to achieve higher recognition accuracy. Tachikawa et al. [5] combined data from an accelerometer, magnetometer, barometer, Wi-Fi module, in addition to the microphone and speaker.
The second factor is the type of localization that is being performed. While the authors of Did you see Bob [1] calculate relative positions in order to enable navigation between two devices, SurroundSense [2] was designed to identify the context in which a device is currently in, e.g. a bathroom or a coffee shop. Batphone [3] and Room Recognize [4] are two examples for applications, that take the approach of SurroundSense one step further and aim at a room-level approach for indoor localization. Therefore, they are able to differentiate multiple rooms of the same type, e.g. bedrooms or meeting rooms.
Although this paper presents a short but detailed overview of different technologies used for indoor localization, it focuses on approaches using audio signals. Room recognition, one area of application of localization, thereby is the main focal point.

Section two briefly lists and describes the most common technologies applicable for indoor localization. Section 3 focuses on active sound fingerprinting explaining the technical background and describing the most promising approaches. Section 4 has the same structure, but for passive sound fingerprinting. To conclude this paper, Section 5 reflects the author's opinion on the state of room recognition using audio signals as of today.

2 Indoor Localization Techniques

To give the reader a better overview of this topic, this section describes multiple techniques used for indoor localization, each with at least one example application. Each technique consists of different hardware, used signals for localization, or both. Even though quite a few signal types applicable for localization exists, only few of them deliver reliable results on their own. But many can help increasing accuracy when used in addition to other signal types. Those complementary types are therefore not listed in particular but mentioned if they have been used by some applications.

2.1 Wi-Fi based localization

Wi-Fi based solutions for localization are among those, that have been around for the longest time that do not require specialized hardware. Ever since the wireless network specification 802.11b has been added to the IEEE 802 set of LAN protocols in the year 1999, wireless LAN has seen a rapid growth regarding the adoption of this technology. Haeberlen et al. [6] published their results regarding indoor localization using the 802.11 wireless network protocol in the year 2004. Under optimal conditions, they achieved a recognition accuracy of 95 percent. However, the result depends on the number of access points available in the building. In their reference office building, which was about 12.500 square meters in size with more than 200 offices and meeting rooms, there were 33 operational access points. With each access point representing

one dimension, they were working with a 33-dimensional signal space. To decrease training time and sample sizes, they treated each room as a single position rather than measuring the signal strength every x meters. This resulted in 510 different locations, where training data had to be collected. The overall training process took 28 man-hours according to Haeberlen et al. [6].
Their system itself mapped the office building as a topological map, with each node representing a specific region, e.g. a certain room. Booij et al. [10] presented in their work, how a topological map of a specific area of a building looks like.

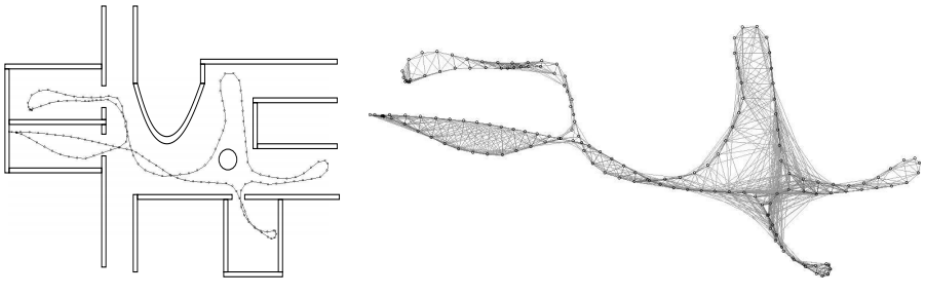


Fig. 1. On the right is an example of how a topological map of the floor inside a building on the left can look like. The line shown on the map on the left represents the taken path by a robot. Images taken from [10].

For localization, the client sends a request package and logs the received response packages. This process is repeated on each of the 11 operational Wi-Fi channels in the US. In Europe, there are 13 active channels available for usage. The system then uses the measured signal strength during this process. In conjunction with the collected training data and the application of the Bayesian localization framework, it is possible to calculate the current client's position.
Since wireless localization can work by only leveraging an existing infrastructure of access points, hence not requiring additional hardware, this technique has been in the focus of many papers. Depending on the use-case, the accuracy which can be achieved by this method might be sufficient. As Liu et al. [11] conducted, current methods can achieve an accuracy of three to four meters. However, Wi-Fi based approaches entail another problem, which might not be acceptable for many scenarios. They all face large error rates from six to eight meters. This error rates mainly results from the fact that many different places exist which exhibit the same signature. Two possibilities to decrease this error rate is to increase the number of active access points or by building a network of clients and incorporate their relative position.

2.2 Acoustic sensing

With the increasing number of smartphones which all have built-in speakers and microphones, acoustic sensing has gained more interest of researchers. If only a

smartphone is needed on the client side, this lowers the barriers of using a system for consumers. Acoustic sensing also enables multiple areas of application.
Song et al. [12] and Rossi et al. [13] developed a system based on acoustic sensing for room-level localization. By leveraging room specific features of echoes, both systems are able to determine the current room the user is positioned in with an accuracy of 89 to 99 percent, depending on the room size, occupancy and background noise. Kunze et al. [14] implemented a method for object localization. Using only a smartphone, they could determine the current location the device is situated in., e.g. if it is lying on a couch or is put inside a drawer. Therefore, they utilized the vibration motor of the smartphone in addition to measuring the response echo of the environment to an emitted sound. Tung et al. [15] presented a possibility for indoor location tagging. This enables a smartphone to detect its position with an accuracy of up to 1cm. This makes use-cases such as enabling Wi-Fi on the smartphone if placed on a certain position available to users. The same can be achieved by using NFC tags, but with additional hardware required.
Regardless which type of localization is being performed, two different methods exists of how acoustic sensing can be carried out. Those two methods are active- as well as passive sound fingerprinting. Passive sound fingerprinting solely relies on measurements of the acoustic background spectrum of rooms. Each measurement result is stored as a fingerprint. From these fingerprints, the system creates a unique room label to later identify a certain room [3]. When performing active sound fingerprinting, the device on the client side actively emits a specific sound through its speakers and measures the corresponding impulse response. Section 3 and 4 describe those two methods in detail.

2.3 With additional infrastructure

While most approaches independent from additional required hardware achieve room- or meter-level localization when being indoors, more precise localization might be necessary or wanted in certain scenarios. Independent of technology, various papers have been published in which the authors achieved accuracy of up to a few centimeters. Liu et al. [16] proofed, that the need for extra hardware must not necessarily lead to an inferior method. While it is indeed true that the client-side is more restricted regarding devices necessary for the localization process, a specialized infrastructure at the location must not have a huge impact for either side. Neither the costs nor the required space are a matter of relative importance for e.g. a large store if the system only requires a few beacons [7, 16, 17] or access points [6, 18]. While Wi-Fi based localization works with most existing infrastructure, the precision can always be increased by increasing the number of access points. Another advantage of these methods is that for most applications no training data must be acquired in advance. It is sufficient if the system knows the location of the hardware inside the building. If that is the case, the location of a device can then be calculated based on the received signals of one or more senders.

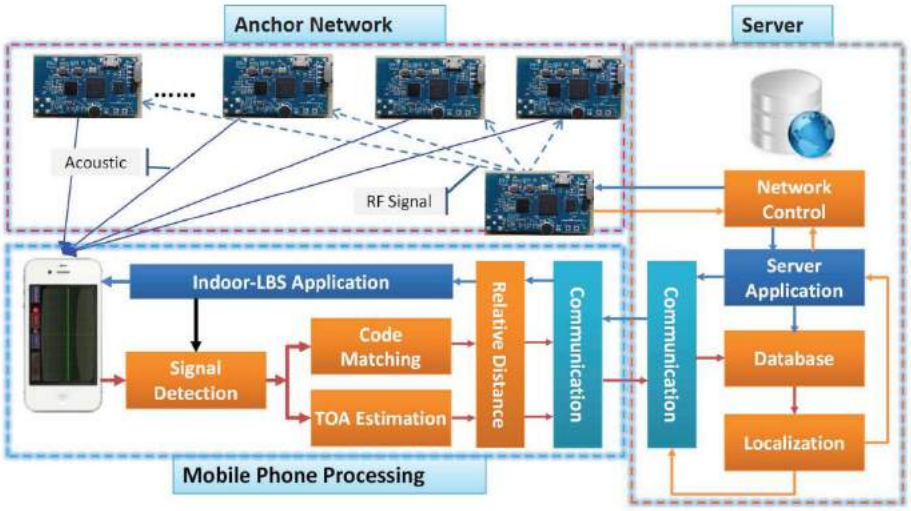


Fig. 2. Architecture of Guoguo [16]

Liu et al. [16] developed a method based on time-of-arrival (TOA) of received signals. It is mandatory for the client device to receive signals from three or more beacons. If that is the case, the device calculates the relative distance to each beacon (node). Each node has a unique ID, which is embedded in the emitted signal. The client in turn sends this information to a server on which the location database of the nodes resides. Based on the fixed location of each beacon and the relative distance of the client to those, multilateration can be performed to find the coordinates, thus the location of the client.

2.4 Doppler Effect

Localization by leveraging the Doppler effect of receiving acoustic signals is a feasible, but rather uncommon solution. Nevertheless, Huang et al. [19] achieved an indoor localization with a mean error in accuracy of just 0.5 meter. The Doppler effect relies on the fact, that waves - in this case sound waves - experience a shortening or stretching if the distance between sender and receiver changes. If the distance gets smaller, the frequency rises. In the opposite case the frequency sinks. Relying on acoustic waves means this method requires some source of emitting devices. Huang et al. [19] therefore used speakers emitting an inaudible sound with a frequency of around 20 kHz. To receive the initial position of the client, there must be at least three speakers (nodes) in range. With the additional use of an accelerometer and a gyroscope in the client's device, it can calculate the direction to each speaker and thereby its position. Any further movement can be measured by the relative displacement to each single node.

6

3 Active sound fingerprinting

As the name suggests, active sound fingerprinting works by emitting sounds of specific frequencies and measuring its impulse response. The frequency differs depending on each approach. While some systems are emitting an – to the human – inaudible sound with a frequency slightly above 20 kHz, devices in other approaches emit audible sounds. Audible frequencies reside between 20 Hz und 20 kHz but slightly vary for each human. Another important aspect of active sound fingerprinting is how to deal with the recorded responses. Various techniques and algorithms therefore exist, each coming with advantages as well as some disadvantages. This chapter describes those technical factors in detail and compares the most promising approaches for room recognition using active sound fingerprinting.
Because acoustic sensing and hence active sound fingerprinting is based on recording, comparing and matching of fingerprints, training data must be collected for each location at which future localization or recognition is intended. However, the required size of training data differs from approach to approach.
This technique is also often combined with different techniques or data from other sensors to further improve accuracy. The implementation of a specific system hence is not limited to just one method.

3.1 Technical background

Frequency. Starting with the choice of frequency, Song et al. [4] investigated the suitability of various frequency ranges in the inaudible spectrum. The results are displayed in Figure 3. Looking at the power of incoming response signals, it is highest for frequencies between around 20 and 20.6 kHz.

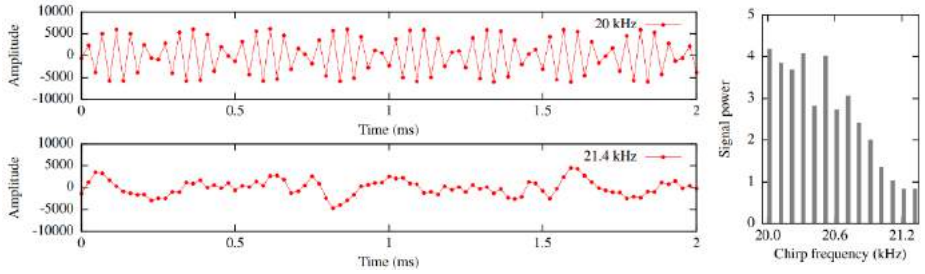


Fig. 3. Representation of the recorded signal (left) and the chirp power (right). Images taken from [4].

For higher frequencies, the power of those chirps dramatically decreases. They also showed that many microphones in modern smartphones cannot well record frequencies well above 20 kHz, thus the signals become distorted. Considering those facts, Song et al. [4] defined 20 kHz as the optimal inaudible frequency for their work.

Tachikawa et al. [5] go for a different approach by playing an audible sound. But instead of limiting the emitted sound to just one frequency, they perform a full sweep from 20 Hz to 20 kHz, thus sampling the full audible range. In order to minimize the impact for users, they limit the sound duration to 0.1 seconds.

Impulse Response Measurement. An accurate measurement of the incoming response to an outgoing audio signal is one of the key tasks in room recognition, because the responds contains specific room features. As a result, many important parameters can be derived from the impulse response. Stan et al. [20] compared the most commonly used techniques for impulse measurement. Among these are the Maximum Length Sequence (MLS) and the Sine Sweep technique. Some given facts apply independent from a specific technique. First, the emitted sound must be remembered and reproducible. Second, for better recognition, the signal-to-noise ratio of the response must be as high as possible. This ratio can be improved by averaging multiple measured output signals before starting with the deconvolution of the response [20].

The MLS is a periodic two-level signal which has a higher power than short impulses by the same output but a longer duration. This results in a better signal-to-noise ratio. The underlying theory is based on the assumption, that MLS works best with linear, time-invariant (LTI) systems. If that is not the case, the impulse responses contain distortion artifacts. An important aspect is that they have almost identical properties as a white noise [21]. An MLS signal of an *M* order in one period has a sample count, thus a length of:

$$L = 2^M - 1 \tag{1}$$

MLS can be generated by using maximal linear feedback shift registers, which recursive function can be displayed as followed [13]:

$$a_m[n+1] = \begin{cases} a_0[n] \oplus a_1[n], & m = 3 \\ a_{m+1}[n], & \text{otherwise} \end{cases} \tag{2}$$

Let the responses of an impulse be h[n] and the MLS be s[n], then the output y[n] is:

$$y[n] = (h*s)\,[n] \tag{3}$$

It is known that the room impulse response can be obtained by circular cross-correlation between the determined output signal and the measured input signal [13]. As a result, when taking the cross-correlation of y[n] and s[n] and assuming that $Ø_{ss}$ is an impulse ($h[n] = Ø_{ys}$), the equation simplifies to:

$$Ø_{ys} = h[n] * Ø_{ss} = h[n] \tag{4}$$

Sine Wave Sweep is a method not dependent on LTI systems, thus better suitable for room-type recognition as carried out in [22]. It uses an exponential sine sweep (ESS) whose frequencies grow with time. The frequency growth rate can be freely chosen.

8

Using this technique, the impulse response (IR) can be deconvolved. Separating each impulse response corresponding to the considered harmonic distortion order is relatively easy because distortions are easy to recognize (shown in Figure 4).

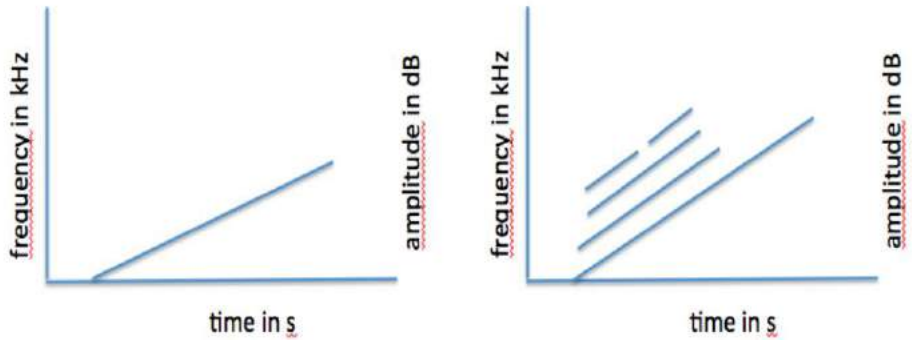


Fig. 4. Exponential Sine Sweep on the left and its measurement with distortions on the right [23]. The upper shorter lines thereby represent the distortions.

The linear impulse response thereby is free from any non-linearity. This is assured because the distortion appears prior to its linear impulse response [20]. Due to the fact that the emitted sweep must extend from 20 Hz to 20.000 Hz, the device emits an audible sound.

Feature Extraction and Classification. Independent from the method of response measurement is the duration of the timeframe that will be recorded. Assuming t=0 marks the beginning of sound emitting, the recording has to start some time around t. Depending on the type of localization, response measurement and many other factors, different durations can be optimal. Most common is a recording length of 100ms to 500ms. To assure that only the echoes get recorded and not the emitted sound itself, many approaches determine a buffer of several milliseconds. Song et al. [4] concluded that not only the emitting time itself should be excluded, but also several more milliseconds, because the response signal in this period is still a lot higher in terms of amplitude as illustrated in Figure 5.

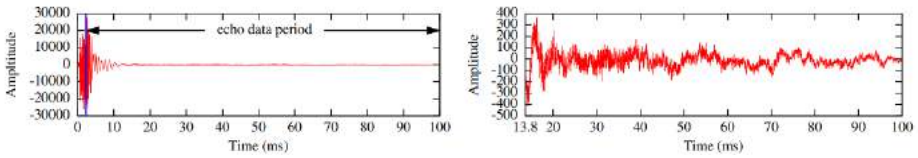


Fig. 5. The entire acoustic trace since t=0 including the emitted sound itself (left). The blue vertical line represents the ending of sound emitting. A zoom-in view of the same signal excluding the buffer of 13.8ms (right). Image taken from [4].

For further processing the complete response is mostly [e.g. 5, 13, 22] processed in multiple frames with a sliding windows of different window size and overlap. To reduce errors and minimize the impact of outliers, each window can get smoothened using a filter, e.g. Hamming Filter.
Common audio features can then be extracted from each frame. Among typical audio features are [24]:

- Spectral flux (SF)
- Auto Correlation Function (ACF)
- Zero crossing rate (ZCR)
- Linear Bands (LINBANDS)
- Logarithmic Bands (LOGBANDS)
- Linear Predictive Coding (LPC)
- Line spectral frequencies (LSF)
- Daubechies Wavelet coefficient histogram features (DWCH)
- Mel-Freq. Cepstral Coefficients (MFCC)

Rossi et al. [13] evaluated many of those features based on their suitability for room recognition. The results are shown in Figure 6.

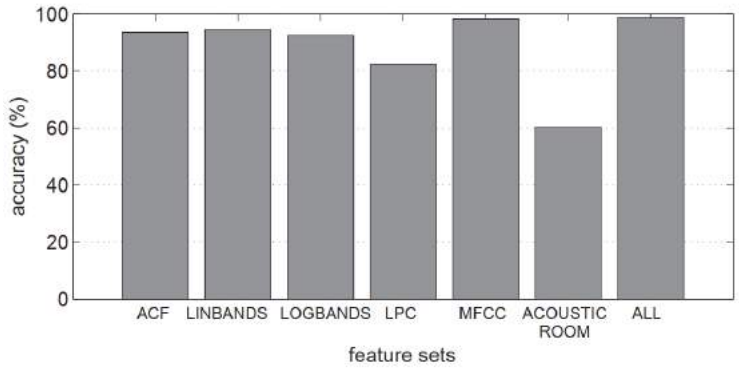


Fig. 6. Performance of various audio feature sets. Image taken from [13]. "ALL" thereby represents a combination of all features.

Since MFCC scored the best results in regard to accuracy among the individual feature sets, it was the feature of choice. MFCC seems to be one of the most useful features, because it is used in most approaches for indoor localization. It is also possible to include multiple features by defining weights for each of them and later calculating a mean score. After extraction, a set of feature vectors f_i exist, with i being the number of defined sliding windows. For better comparability those vectors can furthermore be normalized. Rossi et al. [13] therefore applied the following formula:

$$F_i = \frac{f_i - m_i}{\sigma_i} \tag{5}$$

with m_i being the mean value and σ_i being the standard deviation of all vectors.

The chosen features can now be used for classification. The goal of classification is to use a suitable algorithm in order to gather information from labeled data. It is in addition to Regression one of the two categories of Supervised Learning. The difference is that Regression predicts numerical values while Classification predicts a category for each entry of the dataset. Therefore, many different algorithms exist, e.g. Logistic Regression, K-Nearest Neighbors, Support Vector Machine (SVM), Naive Bayes or decision trees. A general comparison of various algorithms regarding performance can be found in [25]. For room recognition, Tung et al. [15] evaluated different algorithms within the scope of their work and came to the conclusion, that one-against-all SVM performs best. It is a specific implementation of the Support Vector Machine, which in turn is one of the most popular machine learning methods today. Initially designed for binary classification [27], it is the choice in many works about room recognition and indoor localization. Another popular library for SVMs is LIBSVM [26]. Another viable algorithm is Random Forest. Tachikawa et al. [5] are using the Random Forest with custom Decision Trees implemented. The final result then is performed by a majority vote.

Deep Learning. Recent progress in Neural Networks opened another possibility which can replace feature extraction and classification as described above. Since these steps rely on manual feature engineering which deep learning can automate these steps and thus simplify the process. As described in [4], two different types of deep models exist, that are also viable for feature extraction of audio signals. Deep Neural Networks (DNN) and Convolutional Neural Networks (CNN). As described by Krizhevsky et al. [29], CNNs are more flexible, since their depth and breadth can be varied. DNN allows a one-dimensional input only, while CNN can process data coming from multiple input arrays. Both models are already in use for various use cases such as image or language recognition. Song et al. [4] evaluated both in terms of viability for feature extraction of audio signals and concluded, that CNN outperforms DNN. Hence, they are using CNN for further work.
Convolutional Neural Networks consists of a series of stages each with one or multiple layers. The first stages typically consist of two types of layers. Convolutional and pooling layers. Convolutional layers thereby detect local conjunctions of features from the previous layer. Pooling layers work by merge semantically similar features into one feature [28].
A shown in Figure 7, Song et al. [4] implemented two convolutional respectively pooling layer as well as two closing dense layers. The first convolutional layer divides the input image – in case of audio recognition a spectrogram – into 16 multiple smaller images. The first pooling layer in turn applies pooling by sliding a window over each image to gather the maximum pixel value of each subregion as a pixel of the output image. The second conv and pooling layer perform similar actions. The dense layers take on classification with logic integrated for avoiding overfitting by dropping a specific amount of input features.

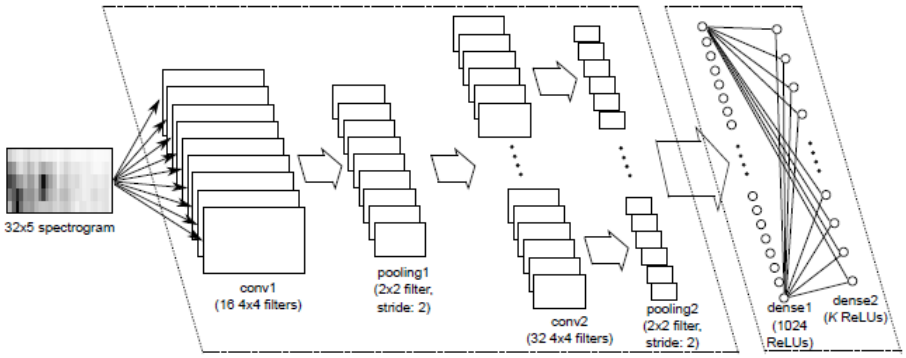


Fig. 7. Structure of the Convolutional Neural Network as used in [4].

As for any neural network, extensive training is required for reasonable results. The choice of Hyperparameters of the algorithm can highly affect the results as well. Number of epochs, Batch size, Number of hidden layers and units, or Weight initialization are some of them. An article on the Towards Data Science Homepage [30] describes the just mentioned hyperparameter and many more in detail.
Since training such a neural network requires extensive amount of processing power, room recognition services using this method rely on a server in the cloud for conducting their work. If not, future localization on the client device would experience much longer processing times as well as a noticeable battery drain.

3.2 Promising approaches

This paper discusses five different approaches for room recognition using active sound fingerprinting. Each of them has been published in a corresponding paper. For comparison and an illustration how accurate localization using audio signals can be, the EchoTag system of Tung et al. [15] is covered in this paper as well.
To give the reader a better overview, Table 1 lists all the approaches covered in this section including the performed type of recognition.

Table 1. Overview of active sound fingerprinting approaches

System	Type of recognition/localization
Predicting Location Semantics [5]	Room type
Restroom Detection [22]	Room type
SurroundSense [2]	Room type / Location
RoomRecognize [4]	Room
RoomSense [13]	Room & Within-Room
EchoTag [15]	Context / NFC-like

Room type recognition. Even though the first 3 methods [5, 22, 2] perform similar recognition, they are not directly comparable regarding their results accuracy. [5] and [22] attempt to recognize specific types of rooms or areas, e.g. restroom or smoking area. The training data of [22] thereby does not include any data from exact locations they later tried to classify. Thus, their system can later theoretically be used at any location of the given type. [5] follows a similar trail. Their sensor data during the training phase is manually collected featuring unknown location classes. As the name suggests, [22] solely focuses on one type of room, that is restrooms. [5] extended their method to six location classes. SurroundSense [2] on the other hand features multiple location types as well but requires previous data collection from each of them. Among those locations are a restaurant, a coffee shop and a grocery store.
In regard to utilized sensors, [5] is the most sophisticated approach. It uses data from a barometer, magnetometer, Wi-Fi signals, as well as acceleration data in addition to the speaker and microphone used for active probing. They detect a place by utilizing acceleration data. If a user stays at the same place for a longer period of time, the localization process gets initiated. The first step is to cluster recognized places based on previously recorded Wi-Fi signals. This step reduces the number of possible places, which are now further analyzed using data from the mentioned sensors. Other benefits of this intermediate step are a reduced error rate in recognition and a faster classification process. Using this method, the authors could achieve an overall classification accuracy F-measure of 78%. Some room types thereby have better accuracies in detection as others. The accuracy of detecting an elevator was about 90% while the desk class often got classified as a meeting room due to similar conditions. They found the active sound fingerprinting as the most helpful input. But using only this data resulted in an accuracy of about 50%. They also conducted that data from the barometric sensor contributed more to the final result than magnetic data. Those results show that despite sound fingerprinting being the most useful input data, combining data from multiple sensors leads to better accuracy in room recognition.
The authors of [22] illustrated, that despite real indoor localization being the more viable approach, room type recognition still has its place for existence. In times of always-on devices getting adopted more widely, there needs to exist a way to exclude certain places from recordings, e.g. sound or video. One of these places are public restrooms, where recordings of any type are not appropriate. In regard to this topic, they developed their system. Unlike the described method of Tachikawa et al. [5], only active sound fingerprinting was used to capture the impulse responses (IR) of each restroom. No other sensors were therefore utilized. In order to better predict real-life performance, the recorded samples of restrooms that are later classified were excluded from the training. They collected IR data from 103 restrooms with 30 samples for each room at different spots inside the location. The results show, that they could achieve an accuracy of above 90% most of the time, depending on which phone was used. Thereby always the same phone was used for recording the training set and later recognition. In order to evaluate their work against its robustness towards background noises, they collected additional data for a restroom. For the new recordings, they varied the occupancy rate from 14% up to 100%. Each person thereby used the restroom as a normal person would including flushing the toilet and washing their

hands. They tested this newly collected data using the same data corpus as before. The achieved results were similar to the previous with an accuracy of above 90%. This experiment proves, that active sound fingerprinting can be robust against various background noises. However, an important aspect the authors worked out within their work is the fact that the accuracy dramatically drops (down to 43%-63%) when different phones are used for collecting the training data and later recognition. For the authors this is attributable to the differences in hard- and software of each phone.
SurroundSense, a relatively old approach by todays standards going back to the year 2009, included data from a light sensor in addition to acoustic data for their recognition technique. They collected data from six distinct places using a Laptop with an additional attached sensor, because smartphones we know today did not exist at that time. However, they already started evaluating their approach on a Nokia N95 device. For localization, they compared the fingerprints of light and sound data with the once previously collected. Therefore, they compared each fingerprint with a "simple matching algorithm" [2], which output is a value of similarity. More precise, it is the inverse of the Euclidian distance. The smaller the distance, the higher the similarity. During evaluation, the output value of the algorithm was the highest for each correct location. In other words, it identified all places correctly. Nevertheless, the similarity value of a location often was almost identical to that of another location. The authors did not state, how their method performs when classifying more than six places or how robust it is against changes in background audio or different light conditions.

Room and within-room recognition. The ability to differentiate between multiple rooms of the same type opens many possibilities, e.g. indoor navigation or tour guides. Two viable solutions for this topic are consecutively described in this chapter. RoomSense [13] and RoomRecognize [4].
The authors of RoomSense aim at not only recognizing specific rooms, but also certain positions within each room. Therefore, they selected 20 rooms and a total of 67 positions at which impulse response data was collected. As the authors stated, that is the equivalent of about one position every $9m^2$. To achieve within-room recognition, two orientations where chosen for each position; towards the center of each room and towards the opposite direction. For each orientation, training data of 40 measurements were carried out, which results in a dataset of 5360 IR measurements in total. For feature extraction and classification, the MLS technique, MFCC, and an SVM classifier (Chapter 3.1) were used. Using all training data, the recognition performance averaged at 98,2%. This high accuracy is based on the high density of training positions which plays an important role regarding the performance of recognition. Figure 8 illustrates the change in accuracy when lowering the density of $9m^2$.

14

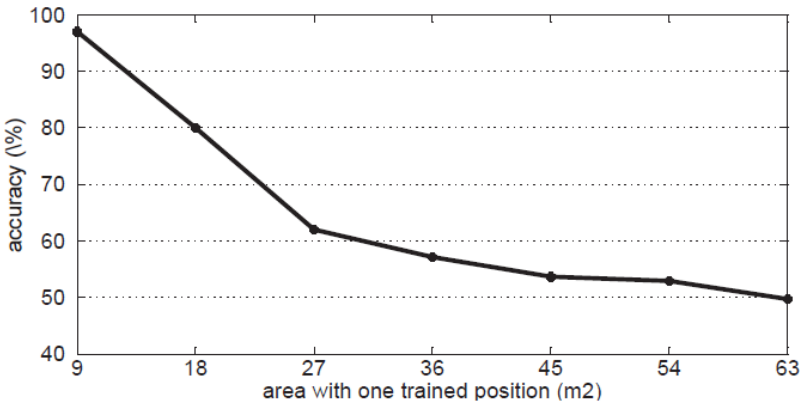


Fig. 8. Impact of lowering the training position density. Image taken from [13].

They also evaluated the robustness of RoomSense against noise. Therefore, they added additive white Gaussian noise to the MLS [31] of the recorded sample data and varied the signal to noise ratio (SNR) from 10dB to up to 50dB. Results drop to about 66% with an SNR of 50dB. Environments with an SNR of 30dB still experience a recognition accuracy of about 85%. This can be explained by the fact, that RoomSense uses the whole audible band from 0-24kHz for the emitted sound. Another side effect of the use of those frequencies is that collecting training samples and later recognition attempts result in an audible process. The architecture of RoomSense is client based, thus no cloud server is required. The computation time for a recognition request is about one second, in theory making this approach suitable for real-time navigation for known and trained locations.

RoomRecognize [4] also achieves high accuracy in room level recognizing. The authors directly compare their results with those of RoomSense, since these are the only two known approaches that exist for this kind of active sound fingerprinting recognition. By emitting inaudible chirps with a duration of 2 milliseconds at a frequency of 20kHz, samples of 50 different locations were gathered and processed by a neural network (Chapter 3.1 – deep learning) to collect fingerprints for each location. The thereby recordings have a duration of 0.1 seconds. Unlike RoomSense, this system is based on a cloud server on which the necessary computation is carried out. It offers a RESTful API for client devices to perform a recognition process. In terms of results, RoomRecognize achieves accuracies of up to 99% as well. Because this approach features a larger dataset of up to 50 rooms, RoomSense achieved a recognition rate of just 83%. These numbers are valid for scenarios without background noise. However, the results of RoomSense in their work must be treated with caution, since there might be a better configuration or setup available. What can be said with certain, is that RoomRecognize is more robust against background noise. While this is a limitation to RoomSense which the original authors mentioned as well, the performance of RoomRecognize does not drop as much. With music playing in the background, the recognition accuracy drops to about 80%. However, the authors did not give any information about the sound level of the background music. The better robustness is - be-

sides the deep learning approach - attributable to the frequency of the emitted sound and the size of the training data set. Because the frequency is in the inaudible range of 20kHz, background music does not interfere as much. The training data set consisted of 22.000 samples, which is four times the size of the data set RoomSense was using. Moving furniture or people walking around could potentially affect accuracy as well. Both represent surfaces that reflect acoustic signals. Song et al. investigated this topic and concluded that their system has a decent loss rate. A small room of $7m^2$ can hold up to three people before performance drops. The same applies for moving chairs or tables. Accuracy drops by a few percent but is still acceptable and better than in case of background music. To test the systems suitability as a tour guide, samples of various exhibition points in museum halls were taken, each about 5 meters apart from another. The authors wanted to know, whether RoomRecognize can distinguish different spots inside a single larger room. The accuracy was 99% for a quiet hall and 89% for a noisy and crowded museum hall.

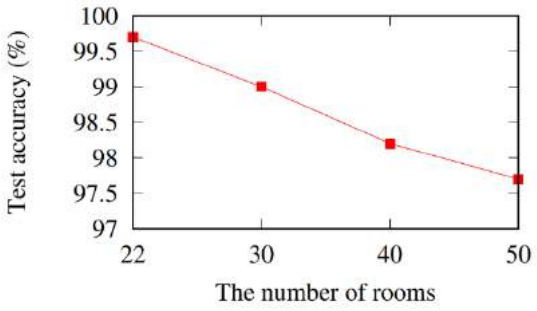


Fig. 9. Influence of room count on the accuracy of RoomRecognize. Image taken from [4].

Both, RoomRecognize and RoomSense lose in accuracy with increasing room count. With more rooms having similar materials and interiors, thus similar fingerprints, differentiation between those is becoming harder if only acoustic data is being used.

EchoTag. Unlike all other approaches mentioned in this chapter, EchoTag [15] follows a different approach. Instead of some sort of room recognition, it recognizes specific locations inside a room with an accuracy of up to 1cm. The authors use this method just like NFC-tags are being used, but without any hardware required. For example, to turn on silent mode if the phone is placed within a certain radius of a previously trained position on the night table. The authors state that it can differentiate between 11 tags with a precision of up to 1cm at 98% accuracy. The reason it is mentioned in this work is to show the reader, how accurate measurements using active fingerprinting can be. The emitted sound has a frequency of 11-22kHz, thus making it audible to people close by. Like many other approaches, EchoTag uses SVM (Chapter 3.1) for later classification. During the recording phase, the system additionally saves the phone's tilt and Wi-Fi signals. It uses those for later computing when to start a localization approach. Only if the phone's tilt and the Wi-Fi signals are similar to a saved entry in the database, the phone starts emitting a sound. A drawback of this

approach is, that accuracy drops over time. Depending on the location by about 40% down to 56%. This is due to indoor activity like removing or adding objects. The authors state that in order to counter this drop in performance continuously training is required.

3.3 Detailed overview of approaches using active sound fingerprinting

For a final overview and better evaluation by the reader, a table with detailed information on the here described approaches is presented (Table 2). The most important distinguishing features are thereby included. However, the overall recognition results are not directly comparable due to multiple facts. First, those numbers represent the results under optimal conditions. Disturbances are not considered in this table, because each approach has its own to deal with, which often differ from the ones another approach has to deal with. Second, the room count included in the training set varies highly. With increasing number of fingerprints collected the accuracy drops. Last, it is not recommended to compare approaches of a different recognition type.

Table 2. Summary of approaches utilizing active sound fingerprinting

	Predicting Location Semantics [5]	Restroom Detection [22]	Surround-Sense [2]	RoomRecognize [4]	RoomSense [13]	EchoTag [15]
Recognition type	Room type	Room type	Room type	Room	Room & Within-Room	Location
accuracy	room-level	room-level	room-level	room-level	300cm	1cm
Number of rooms	6 classes 24 rooms	103 + non restrooms	6	50	20	11 tags
Data set size	N/A	7.474	N/A	22.000	5360	N/A
Feature extraction & classification	MFCC, Random Forest	MFCC, LibSVM	Euclidian distance	Deep Learning	MLS, MFCC, SVM	N/A, SVM
Architecture	client	client	client	client-server	client	client
Emitted sound duration & frequency	100ms SineSweep *	100ms SineSweep *	N/A 20-250Hz	100ms 20kHz	680ms 0-24kHz	420ms 11-22kHz
Sensors used	Microphone Speaker Barometer Magnetometer Wi-Fi Accelerator	Microphone Speaker	Microphone Speaker Light	Microphone Speaker	Microphone Speaker	Microphone Speaker Wi-Fi Gyroscope

Year	2016	2014	2009	2018	2013	2015
Overall recognition results **	85%	>92%	100%	>99%	98% room 96% within-room	98%

* A SineSweep sweeps frequencies from 20Hz to 20 kHz
** Results for recognition under optimal conditions.

RoomRecognize [4] is listed with a room-level accuracy, even though they applied their method in museums to recognize certain exhibition points with an in-between distance of several meters. Thus, one could argue that the application has an accuracy of about 5 meters. However, because the authors themselves did not conduct within-room testing for smaller rooms like offices or restrooms, the accuracy is set to the given value.

4 Passive sound fingerprinting

The passive sound fingerprinting technique works by not emitting any sound, but instead listening to foreground and background noises of a room. In general, approaches using this technique achieve lower accuracy than those using active sound fingerprinting. Thus, not as many systems capitalize on this method for room recognition. Batphone [3] and SurroundSense [32] are the only two systems that are known to the author that do not require additional hardware. To eliminate ambiguities regarding SurroundSense because it is also listed in the previous section, it must be said that the authors developed another system having the same name. They refined their previous work [2] and published their results several months later [32].

4.1 Technical background

While SurroundSense uses a technique based on the Euclidian metric which has been described in Chapter 3.1, Batphone uses a technique based on the Acoustic Background Spectrum (ABS) which is described below.

Acoustic Background Spectrum (ABS). ABS represents an ambient sound fingerprint of a certain room. In order to compute the ABS of a room, an audio sample must be recorded. The sample then is transformed into a time-frequency representation called a power spectrogram [3]. Next, background sound levels are extracted from the spectrogram and stored as a vector. Finally, the logarithm of this vector is calculated to receive the fingerprint in decibel (dB) units. Figure 10 shows the procedure of the described process. Classification can now be performed based on the obtained fingerprints.

18

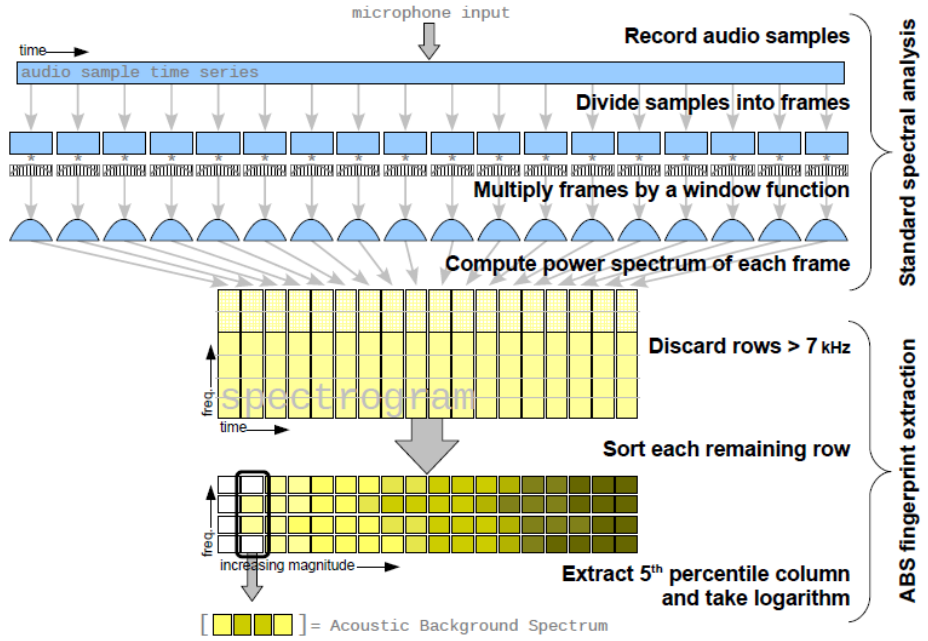


Fig. 10. Steps performed for calculation of an ABS. Image taken from [3].

In order to calculate the power spectrogram, several steps must be performed. First, the recorded sound has to be divided into frames of a certain length. To reduce the signal magnitude in each frame at the boundary, each frame is multiplied by a window function vector. Next, the power spectrum is calculated for each frame. This process consists of three steps:

1. A fast Fourier transform (FFT) is applied. FFT is an algorithm, with which a digital signal can be fragmented into its frequency domains [33].
2. The resulting redundant second half is discarded.
3. To receive the power, each result element is multiplied by its complex conjugate.

Now, that the spectrogram is calculated, the needed frequency band can be extracted. In case of Batphone, it is the 0-7kHz band. Therefore, the corresponding rows are isolated.
Permanent present sounds are equally present in all rows of the power spectrogram. Temporary sounds however are only present in a small number of the time columns and should be filtered out in order to achieve better noise robustness. Therefore, the authors of Batphone sort each row by increasing magnitude and then only select the bins within the 5 percent quantile. This way it can be assured that most transient sounds are eliminated and only the background sound level is extracted, making the fingerprint time-invariant.

Classification of ABS room fingerprints. For fingerprint matching of a future recognition request, Classification must be performed. Batphone therefore utilizes supervised learning. First, the vector Euclidian distance is chosen as the distance metric for comparing fingerprints. The nearest-neighbor technique is then used to select the fingerprint with the smallest Euclidian distance from the database which holds all collected fingerprints. This selection process to find the room label of the closest fingerprint can mathematically be described as follows:

$$roomlabel_{best} = \underset{X \in T}{argmin} \sqrt{\sum_{l=1}^{L} (fp_i[l] - fp_{new}[l])^2} \quad (6)$$

With L being the number of fingerprints in the database and fp_{new} the fingerprint to match. X presents the set of collected fingerprints with their corresponding room label:

$$(fp_i, \text{roomlabel}_i) \in T \quad (7)$$

One drawback that the authors state using the nearest-neighbor method is that the query time for each localization requests grows with the database size, thus potentially becoming a bottleneck. However, with a dataset of a few hundred or thousand collected fingerprints performance is not yet affected.

4.2 Approaches using passive sound fingerprinting

Batphone [3] and SurroundSense [32] are both approaches using the passive sound fingerprinting technique. While Batphone solely relies on sound data and Wi-Fi signals, SurroundSense utilizes various sensors for room recognition. Also, SurroundSense performs room-type recognition. It can therefore differentiate between shops, pubs, any many more. Batphone on the other hand was designed to recognize specific rooms out of a set of multiple rooms of the same type. Both applications are described more precisely in this chapter.

Batphone uses ABS fingerprinting (Chapter 4.1) to identify each specific room. It achieves an accuracy of 69% on a dataset consisting of 43 rooms and five room types. For training data collection, the authors collected a 30 second WAV file recording (24bit at 96kHz) at four different locations in each of the 43 rooms. To make their system more robust, they visited each room two times on different days, which makes a total of eight recordings per room or 344 samples altogether. Office, lounge, computer lab, classroom, and lecture hall are the five room types to which a room can be assigned to. Each ABS fingerprint had a file size of 1.3kB. To create a Wi-Fi fingerprint, the authors used Apple's core location service which is built into the IOS operating system. It returns a coordinate (longitude and latitude) for a given Wi-Fi RSSI. This coordinate represents the fingerprint. In quiet environments, an average recognition accuracy of 69% could be achieved by combining both fingerprints. As the authors state, their system is susceptible to background noises such as conversations, chatters, or even a climate control. Depending on the room type and background noise, accuracy dropped down to 3, respectively 0% in the worst-case. This was the case in a lecture hall during conversations of students and chatters, when people were

leaving the lecture hall. However, for other rooms the drop in accuracy is not as dramatic so that a positive recognition is still possible in 50% of the cases. The loss of accuracy can be reduced by switching from the 0-7kHz band to the 0-300Hz band, but then recognition accuracy in a quiet environment is lower. Thus, it must be decided whether recognition in quiet places or recognition in noisy places is the focus.
SurroundSense [32] follows a different approach by using the audio data solely as a filter and therefore utilizing many more sensors. For data from each sensor a unique fingerprint is created. Each location consists of a set of four fingerprints created from different data:

1. Ambient sound. The fingerprint creation is based on the Euclidian metric (Chapter 3.1).
2. Accelerometer. By sampling the accelerometer four times per seconds, a moving average of the last 10 collected samples is generated. A support vector machine (Chapter 3.1) is used to classify each sample as either moving or stationary.
3. Color/Light. By extracting color and light intensities using the phone's build-in camera, a fingerprint can be created.
4. Wi-Fi. For creation of a Wi-Fi fingerprint, the MAC addresses of access points in range are used. Based on the relative frequency a MAC address was present during all recordings. The result is a fraction, which is stored in a tuple with other fractions for that place. This tuple forms the fingerprint.

To then match a fingerprint, the stored Wi-Fi, sound, and accelerometer fingerprints are used to filter the data set. This safely eliminates most entries present in the database. The remaining set of entries is then used to match the color and light data with those of the new fingerprint. The output is an ordered list of possible places where the user is likely to be. Using this method, SurroundSense has an accuracy of 87% when differentiating between 51 different locations. As previously mentioned, this approach performs room type recognition and is therefore able to recognize different shops like a Starbucks store or a Chinese restaurant, but not rooms of the same type. SurroundSense has a client-server architecture, meaning the collected data is preprocessed on the phone in order to reduce the required data volume and then sent to a server where classification is being performed. One drawback of utilizing the color and light data as the main source for matching fingerprints is that the camera on the client's phone must be enabled all the time. This will result in a high battery drain on any smartphone, although the authors did not mention this topic. Also, the authors did not experiment with different sizes of the training set. They always used the recorded data from all 51 stores. The change of recognition accuracy with increasing location count would be a useful information.

4.3 Detailed overview of approaches using passive sound fingerprinting

Both approaches are summarized in this chapter in regard to the most relevant distinctive features of the passive sound fingerprinting technique. The overall recognition

accuracy of Batphone shows, what the authors of SurroundSense state. Relying mostly on ambient sound for localization does not deliver satisfactory results. For one thing, background noises are very likely to change over time. And secondly, this technique is very vulnerable to any source of noise that appears during recording. Nevertheless, ambient sound can improve results when utilized as an additional data source.

Table 3. Summary of approaches utilizing passive sound fingerprinting

	Batphone [3]	SurroundSense [32]
Recognition type	Room	Room type
accuracy	room-level	room-level
Number of rooms	43 locations	51
Data set size	344	N/A
Sound feature extraction & classification	ABS, Euclidian distance	Euclidian distance
Architecture	client	client-server
Sensors used	Microphone Wi-Fi	Microphone Wi-Fi Accelerator Camera
Year	2011	2009
Overall recognition results *	69%	87%

* Results for recognition under optimal conditions.

5 The author's opinion

A note before proceeding. This chapter reflects the author's opinion and may differ from some of the readers. The evaluation is performed in regard to the suitability of a multi environment usage of those approaches.
To summarize briefly: The published approaches that do not require additional hardware do not have the potential for a break-through in large-scale room recognition or even indoor navigation as of today. Even though many achieve good recognition accuracy in specific environments, they are not applicable for a more widespread use.

However, some [4,13] are accurate enough to be used as a tour guide in a museum for example.
The same applies for approaches that require an additional infrastructure, e.g. beacons or access points. Despite their accuracy - of up to a few centimeters - being nearly perfect, it is simply not feasible to assume that a large number of different types of locations (universities, shopping malls) all install the same hardware and link their systems, so that a user only needs one application for room recognition.
Comparing results of the active and passive sound fingerprinting technique, first outclasses the passive method in all respects. Because active sound fingerprinting does also work when using inaudible frequencies above 20kHz, there is no drawback in using the active fingerprinting technique.
One problem all approaches that mostly rely on acoustic data are facing is their decreasing accuracy with an increasing data set size and time passing by. With more and more rooms having similar acoustic features, differentiating those is getting harder. Also, a room's acoustic properties are likely to change over time due to different background noises or moved interior like chairs or tables.
The authors of [5] and [32] show, that utilizing multiple sensors of a modern smartphone increases accuracy and can help to counter the mentioned loss in accuracy. Especially data collected from Wi-Fi signals and the barometer seem to be a useful addition.
For a future break-through of this technology, several aspects must be considered. As of today, the user will have to install a separate app for each location that supports room recognition. This is a major drawback. On the other hand, it is unlikely that any company will get access or has the manpower to take samples of many locations around the world. Another obstacle will be privacy. Especially in European countries, any company taking audio recordings of several seconds will likely violate multiple laws. Therefore, another solution must be found. A publicly available global database of room fingerprints to which anybody can contribute to would be one solution. Therefore, multiple steps have to be performed and implemented.
First, a defined standard for a fingerprint representation must be composed. Second, an open-source mobile application must be published, so that any user can record and upload fingerprints to the database. The open-source aspect thereby is important to eliminate any concerns about what computation is done with the gathered data. With more and more global players like Google or Microsoft contributing to the open-source community, this should not be a problem.
Any company developing an application for room recognition can now pull the global collection of fingerprints. With an appropriate standard for fingerprint representation, meaning it includes data from multiple sensors and location data, the company can then develop their own algorithms for better accuracy. Another option made possible tis way is to include room recognition into existing services.
This proposal would allow competition on the market while benefiting the end user at the same time. Since all developers have access to the same data, those creating the best algorithms for recognition are in advantage. End users can choose between multiple applications, but regardless of their location only one is required.

References

1. Ionut Constandache, Xuan Bao, Martin Azizyan, and Romit Roy Choudhury: Did you see Bob?: human localization using mobile phones. In: MobiCom 2010, pp. 149–160 (2010).
2. Martin Azizyan, and Romit Roy Choudhury: SurroundSense: mobile phone localization using ambient sound and light. In: ACM SIGMOBILE Mobile Computing and Communications Review, Volume 13 Issue 1, pp. 69-72 (January 2009).
3. Stephen P. Tarzia, Peter A. Dinda, Robert P. Dick, and Gokhan Memik: Indoor localization without infrastructure using the acoustic background spectrum. In: Proceedings of ACM MobiSys 2011, pp. 155–168 (2011).
4. Qun Song, Chaojie Gu, and Rui Tan: Deep Room Recognition Using Inaudible Echos. In: Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, Volume 2, No. 3, Article 135 (2018).
5. Masaya Tachikawa, Takuya Maekawa, and Yasuyuki Matsushita: Predicting location semantics combining active and passive sensing with environment-independent classifier. In: UbiComp '16 Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing, pp. 220-231 (2016).
6. Andreas Haeberlen, Eliot Flannery, Andrew M. Ladd, Algis Rudys, Dan S. Wallach, and Lydia E. Kavraki: Practical robust localization over large-scale 802.11 wireless networks. In: MobiCom '04 Proceedings of the 10th annual international conference on Mobile computing and networking, pp. 70-84 (2004).
7. Roy Want, Andy Hopper, Veronica Falcão, and Jonathan Gibbons: The active badge location system. In: ACM Transactions on Information Systems (TOIS) Volume 10 Issue 1, pp. 91-102 (1992).
8. I. Constandache, S. Gaonkar, M. Sayler, R. R. Choudhury, and L. Cox: EnLoc: Energy-efficient localization for mobile phones. In: IEEE INFOCOM 19-25 April 2009 (2009).
9. European Global Navigation Satellite Systems Agency Homepage, https://www.gsa.europa.eu/european-gnss/galileo/galileo-european-global-satellite-based-navigation-system, last accessed 2019/06/24.
10. O. Booij, B. Terwijn, Z. Zivkovic, and B. Krose: Navigation using an appearance based topological map. In: Proceedings 2007 IEEE International Conference on Robotics and Automation (2007).
11. H Liu, Y Gan, J Yang, S Sidhom, Y Wang, S Sidhom, Y. Wang, Y. Chen, and F. Ye: Push the limit of WiFi based localization for smartphones. In: Mobicom '12 Proceedings of the 18th annual international conference on Mobile computing and networking, pp. 305-316 (2012).
12. Q Song, C Gu, and R Tan: Deep Room Recognition Using Inaudible Echos. In: Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies Volume 2 Issue 3 (2018).
13. M Rossi, J Seiter, O Amft, S Buchmeier, and G. Tröster: RoomSense: an indoor positioning system for smartphones using active sound probing. In: AH '13 Proceedings of the 4th Augmented Human International Conference, pp. 89-95 (2013).
14. Kai Kunze and Paul Lukowicz: Symbolic Object Localization Through Active Sampling of Acceleration and Sound Signatures. In: UbiComp 2007: Ubiquitous Computing, pp. 163-180 (2007).
15. Yu-Chih Tung and Kang G. Shin: EchoTag: Accurate Infrastructure-Free Indoor Location Tagging with Smartphones. In: MobiCom '15 Proceedings of the 21st Annual International Conference on Mobile Computing and Networking, pp. 525-536 (2015).

16. Kaikai Liu, Xinxin Liu, and Xiaolin Li: Guoguo: Enabling Fine-grained Indoor Localization via Smartphone. In: MobiSys '13 Proceeding of the 11th annual international conference on Mobile systems, applications, and services, pp 235-248 (2013).
17. Nissanka B. Priyantha, Anit Chakraborty, and Hari Balakrishnan: The Cricket Location-Support System. In: MobiCom '00 Proceedings of the 6th annual international conference on Mobile computing and networking, pp. 32-43 (2000).
18. Paul Castro, Patrick Chiu, Ted Kremenek, and Richard Muntz: A Probabilistic Room Location Service for Wireless Networked Environments. In: UbiComp 2001: Ubicomp 2001: Ubiquitous Computing, pp. 18-34 (2001).
19. Wenchao Huang, Yan Xiong, Xiang-Yang Li, Hao Lin, Xufei Mao, Panlong Yang, and Yunhao Liu: Accurate Indoor Localization Using Acoustic Direction Finding via Smart Phones. In: Proc. of IEEE INFOCOM (2014).
20. GB Stan, JJ Embrechts, and D Archambeau: Comparison of different impulse response measurement techniques. In: Journal of the Audio Engineering Society Volume 50 Issue 4, pp. 249-262 (2002).
21. LiveScience Homepage, https://www.livescience.com/38387-what-is-white-noise.html, last accessed 2019/06/29.
22. Mingming Fan, Alexander Travis Adams, and Khai N. Truong: Public Restroom Detection on Mobile Phone via Active Probing. In: ISWC '14 Proceedings of the 2014 ACM International Symposium on Wearable Computers, pp. 27-34 (2014).
23. Franco Policardi: MLS and Sine-Sweep technique comparison in room-acoustic measurements. In: ELEKTROTEHNIŠKI VESTNIK 78(3) ENGLISH EDITION, pp. 91-95 (2011).
24. Dalibor Mitrović, Matthias Zeppelzauer, and Christian Breiteneder: Features for Content-Based Audio Retrieval. In: Advances in Computers, pp. 71-150 (2010).
25. Rich Caruana, and Alexandru Niculescu-Mizil: An empirical comparison of supervised learning algorithms. In: Proceeding ICML '06 Proceedings of the 23rd international conference on Machine learning, pp. 161-168 (2006).
26. CC Chang, and CJ Lin: LIBSVM: A library for support vector machines. In: ACM Transactions on Intelligent Systems and Technology Volume 2 Issue 3 (2011).
27. Y Liu, and YF Zheng: One-against-all multi-class SVM classification using reliability measures. In: Proceedings. 2005 IEEE International Joint Conference on Neural Networks (2005).
28. Yann LeCun, Yoshua Bengio, and Geoffrey Hinton: Deep learning. In: Nature 521, 7553, pp. 436–444 (2015).
29. A Krizhevsky, I Sutskever, and GE Hinton: ImageNet Classification with Deep Convolutional Neural Networks. In: Advances in Neural Information Processing Systems 25 (2012).
30. Towards Data Science Homepage, https://towardsdatascience.com/a-walkthrough-of-convolutional-neural-network-7f474f91d7bd, last accessed 2019/07/01.
31. London South Bank University, Shafiul Alam: Assignment on: Effect of Additive White Gaussian Noise (AWGN) on the Transmitted Data, https://pdfs.semanticscholar.org/0320/f32a1580fc1f3bf5f015b7eefefcfc9d10c4.pdf (2008), last accessed 2019/07/02.
32. Martin Azizyan, Ionut Constandache, and Romit Roy Choudhury: SurroundSense: mobile phone localization via ambience fingerprinting. In: MobiCom '09 Proceedings of the 15th annual international conference on Mobile computing and networking, pp. 261-272 (September 2009).

33. W.T. Cochran, J.W. Cooley, D.L. Favin, H.D. Helms, R.A. Kaenel, W.W. Lang, G.C. Maling, D.E. Nelson, C.M. Rader, and P.D. Welch: What is the fast Fourier transform?. In: Proceedings of the IEEE Volume: 55, Issue: 10, pp. 1664-1674 (1967).

Ubiquitous Object Imaging Using Audio Signals

Julian Westermann, Long Wang

Karlsruhe Institute of Technology - KIT
uenkw@student.kit.edu, wanglong@teco.edu

Abstract. Object imaging is a field of research that is important for a various number of applications. A popular acoustic imaging technique is the ultrasound (US) imaging technique used for medical diagnosis. Because in todays society almost everybody owns an ubiquitous device aka smartphone there is a founded interest in bringing imaging techniques to the smartphone. As an example this allows to perform medical ultrasound based diagnosis in urgent situations like at the scene of an accident. As taking images with a camera is widely used an alternative might be acoustic imaging. This paper will present imaging techniques that are based on acoustic signals like US. For the most of these examples dedicated hardware is needed to extend the smartphones functionality. However there is one approach that only uses a smartphones built-in speaker and microphone. By presenting these techniques it is shown that todays smartphones are already powerful enough to perform the task of object imaging.

1 Introduction

Camera based imaging is widely used and enjoys great popularity. However this imaging approach still lacks in quality when it comes to taking images at dark places. This is only one property where acoustic based imaging is superior to camera based imaging. Because acoustic signals are not dependent on lighting condition they can be used for taking images in dark places, for example in a cave or at night. Furthermore acoustic signals can propagate around obstructions which allows to see around corners[1] and they can penetrate materials allowing to detect weapons hidden under clothes[2].

When it comes to fields of application smartphone based acoustic imaging has a broad spectrum of use cases. By bringing ultrasound diagnosis to a mobile device usage in urgent situations like the scene of an accident or on a battlefield can become possible. Obstacles in dark places like a cave can also be detected when using acoustic signals and can thereby help to navigate through situations with bad lighting conditions. At an airport or at crowded places like concerts an acoustic based imaging technique can help to detect weapons hidden under clothes like mentioned befor. However the advantage is hereby that it can complement commodity security scanners by detecting non-metallic weapons. At last it is also possible to detect the wear level of a tool and thereby be able to decide if it needs to be replaced or is still fully functional.

2 Ultrasound imaging

This section will introduce four researches using US probes for object imaging. These probes can be connected to a PC, tablet or smartphone. Ultrasound probes are popular because the technology is known for a while and "Ultrasonography became an important tool of medical imaging diagnosis"[3]. This makes them very attractive to be used with mobile devices to allow field use.

2.1 How ultrasound imaging works

Because some characteristics of US imaging are mentioned later in this paper, this section will briefly explain the underlying technique of US based imaging. First of all there are three imaging modes that are to be distinguished: *A-mode*, *B-mode* and *C-mode*.

A-mode A-mode US imaging can be seen as the generation of raw analog data. When a transducer sends ultrasound waves these waves "propagate through the different media being imaged, and then return to the transducer as "reflected echoes""[4]. An echo is produced when the ultrasound waves pass from one substance to another substance with a different acoustic impedance. The impedance is "linked to the density of the medium"[5]. Fluids produce no echoes because they do not create an acoustic difference that leads to echoes[5]. The echoes are transformed into electrical signals that can be used to process an image[4]. Fig. 1 shows how the reflected echoes can be converted into a signal. The strength of the produced echo depends on the medias impedance. The higher the signal peak, the stronger the echo. This imaging mode allows to measure the lengths. For example it can be used to measure the diameter of an eye. In Fig. 1 the lengths can be taken as the differences between the echoes, named as Ep and D. The third peak of the right signals is lower, because a part of the US waves were reflected when they met the object at distance D.

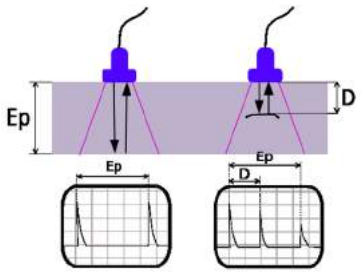


Fig. 1. A-mode ultrasound imaging[5]

B-mode B-mode US imaging is similar to A-mode imaging but maps the height of a peak to brightness. For example a low peak would be a dark pixel and a height peak would be a bright pixel. Fig. 2 shows how a mapping can be done[6]. However this mapping alone does not count for much which means that the scan needs to be done again at different levels of the object in order to be able to get an image.

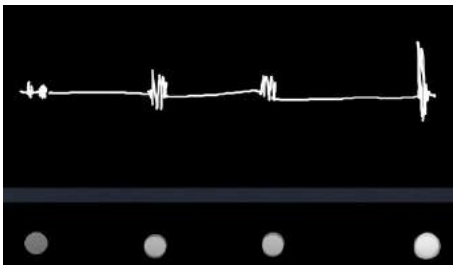


Fig. 2. Mapping of peaks to pixels[6]

C-mode C-mode US imaging allows to visualize the blood flow in the human heart. This is done by encoding doppler information with color. These colors are then used as an overlay for the corresponding image. Typically two colors, red and blue, are used to show the blood flow. Red symbolizes blood flow away from the transducer and blue symbolizes blood flow towards the transducer. The shades of these two colors "are used to display velocity"[7] where a lighter shade displays a higher velocity[7]. Fig. 3 shows an example of a US image with C-mode overlay.

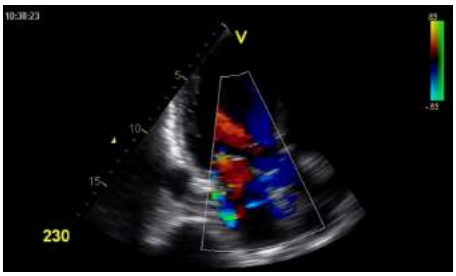


Fig. 3. C-mode image example[7]

As mentioned in B-mode explanation the mode alone only gives some help to render an image but a single sample as seen in Fig. 2 is not sufficient. Therefore

it is necessary to repeat the imaging procedure at different spots or by tilting the transducer left and right to get more samples and thereby creating an image. For tilting the transducer there are two possible ways as can be seen in Fig. 4 and Fig. 5.

Fig. 4. Manual sweeping[6]

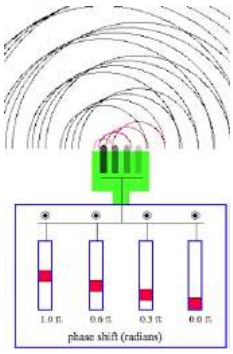


Fig. 5. Virtual sweeping by using more channels and phase shift[6]

Fig. 4 shows an image that has been created by manuelly tilting the transducer left and right, thereby producing an image using the B-mode scan.
Fig. 5 shows how 4 piezoelement elements (4 channel transducer) can be used to create the same effect as in Fig. 4. The 4 channels are used in a way that not all send at the same time. Moreover the elements are used with a phase shift. This means that as in Fig. 4 the first channel is delayed by π, second by 0.6π, third by 0.3π and the fourth is not delayed at all. These different delays create a wave barrier that is moving from left to right as the channel delays change over time. This method is called beamforming.

2.2 Introduction of probes

In this section I introduce the probes and give information about **Application, Usability, Connectivity and Processing** where possible.

2.2.1 Smartphone-based Portable Ultrasound Imaging System[3]: The first probe that shall be introduced is a prototype probe from Seewong Ahn et al. Their "smart US imaging system (SMUS)"[3] consists of a Samsung Galaxy S5 and a self developed 16-channel probe. Fig. 6 shows the probe connected to the smartphone.

Application
The application scenario for this probe is "point-of-care diagnosis"[3]. It is

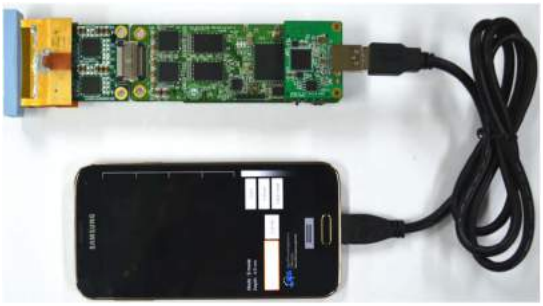


Fig. 6. Smart US imaging system[3]

meant to support point-of-care diagnosis by supplying a probe that can provide real-time images. Its need is justified by lining out that commercial systems exist but are either too heavy in weight or do only provide a small 3.5 inch display with low resolution.

Connectivity
Fig. 6 shows that the probe provides an interface to connect to a processing device. The probe can be connected using the USB 3.0 protocol. This interface is sufficient to provide 58 fps real-time B-mode imaging.

Processing
The probe performs "beamforming and mid-processing procedures"[3]. Processing, image rendering and displaying is done on the Galaxy S5. Generation and processing of samples is divided into four sections: *Analog front-end*, *Digital front-end*, *Mid processing* and *Back-end processing*.
Fig. 7 includes all of these four sections. The *analog front-end* consists of two 8-channel pulsers, as well as ADC and noise amplifiers. This front-end has a sampling frequency of 40MHz. Its task is to generate US pulses. The controlling task when to send out these pulses is taken by the digital front-end. It is also the digital front-end that receives the signal echo after being processed by the amplifier and Analog-to-Digital-Converter. It an be seen as blocks *Analog Front-end Chip* and *Pulser Chip*.
Digital front-end is divided into transmit beamformer, controlling the transmission of US signals, and receive beamformer that receives the signals converted by the analog front-end. It is located in the *FPGA*-block.
Mid processing has the task of filtering and demodulation of the signal that it receives by the digital front-end. This processing is done in hardware on the probe itself and can be found in the *FPGA*-block as well. After that the data is then sent to the smartphone via USB interface.
The smartphone is the last processing section; *back-end processing* as represented by the block named *Smart Device*. The processing uses the smartphones GPU with OpenGL 3.0 to generate the B-mode image. Unfortunately

there was no detailed description of image processing algorithm.

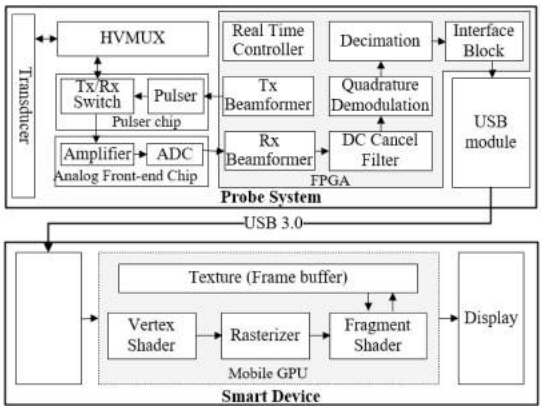


Fig. 7. Processing of SMUS-system as block diagram[3]

Usability
The authors state that B-mode imaging has a depth of 4cm with a maximum frame rate of 58 fps. These specifications are "sufficient to provide subtle temporal change of the biological tissue being examined"[3]. With a fully charged battery of the Galaxy S5 the system can be used to up to 54 minutes. Power consumption lies at 8.16W. Safety regulation ("IEC 60601-1"[3]) for devices having contact with a patient require that eletronical parts must not exeed a temperature of 43°C. The system satisfies this regulation, producing a maximum temperature of 35°C. In contrast to commercial probes that were mentioned earlier this probe only weights 180g.

2.2.2 Color Doppler Imaging[4]: This paper complements the previously introduced paper or probe by giving information about using color doppler with the probe.

Application
Color dopper (or C-mode) makes it possible to not only see an US scan but add color information to it. That means that a C-mode scan can show "the velocity and the distribution of the blood flow in human body"[4] and therfore provide important additional information when it comes to "diagnose the hemodynamic status of the injured patient"[4].

Connectivity
Because this system is the same as the previous one there can not be any

new information stated.

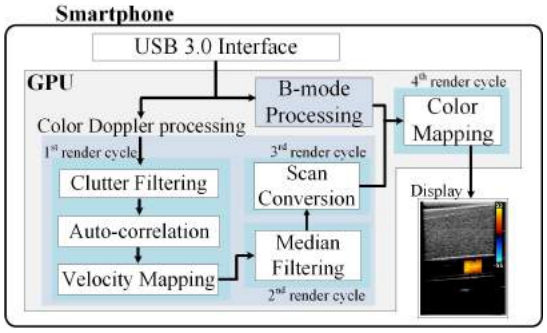


Fig. 8. C-mode[4]

Processing
The concept of processing by four sections as seen in Fig. 7 stays the same. Also processing is done on the smartphone GPU using OpenGL ES 3.0. The aspect that changed is how the received data from the probe is processed in the GPU. To see what C-mode does, have a look on the processing diagram of B-mode in Fig. 7 and the C-mode in Fig. 8.
Note here that the *B-mode Processing* block in Fig. 8 references to the *Mobile GPU* block in Fig. 7. As one can see the data from the probe is not only processed as B-mode, but also as C-mode which means that one gets two images from the same data. The C-mode image is then overlaid on the B-mode image which is seen as the *Color Mapping*.

Usability
When compared to B-mode the probe operated in C-mode has a lower frame rate of up to 20.3 fps (B-mode: 58 fps) which is caused by higher computing costs. The probe still operates in real-time for the data size stays the same for B-mode and C-mode imaging. Therefore the processing time of B-&C-mode imaging is fixed at 22.14ms. The frame rate in contrast depends on the view depth. Because with increasing view depth the round trip time of the transmit ultrasound increases, the frame rate decreases accordingly.

2.2.3 Arduino-like Development Kit[5]: The paper about Arduino-like Development Kit tries to give a manual for students, researchers or ultrasound enthusiasts to build their own ultrasound imaging system. It provides several repositories on github and a more detailed documentation to help getting started with a self-made US system. The goal of this project is not to develop or design

an ultrasound probe like the ones in the previous sections, but "to provide a basic open-source tool to understand ultrasound imaging technique"[5]. To give a user the ability to replace special parts of the system the paper followed a modular approach where core tasks can be performed by different chips, modules, etc. Fig. 9 shows an image of the system with the modules necessary for US imaging.

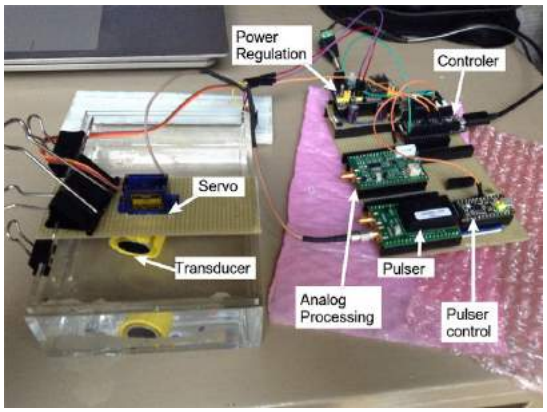


Fig. 9. Setup of US system with single channel transducer[5]

Application
As stated above this system is meant to be a project for students, researchers or enthusiasts. It is not tested to satisfy regulations needed to be used in a medical szenario. This is because when used in medical application a probe will be applied to human patients and must therefore proof that it is safe against "overheating, and mechanical breaking of tissue structures"[5].

Connectivity
The system uses a Arduino-IDE-compatible micro-controller and is able to stream data over wifi. Any "wifi-enabled device can acquire the UDP stream"[5].

Processing
This system does not return an image as a result of processing. Though it does process the raw data in the "Analog Processing Module"[5] it returns a digital output. This digital output is then sent via wifi to be processed into an image or any other form of further process. To categorize the data, the system operates as a A-mode ultrasound probe as explained in section 2.1.

Usability
Because this system comes with a single piezoelement (single-channel) beamforming overhead is avoided. This also means that this system needs a servo

motor to rotate the transducer in order to produce a set of data for image processing. Some drawback of so called mechanical probes is "slow scanning, mechanical fragility and insensitivity"[5]. The imaging depth that can be achieved is 230mm. Frame rate can be increased by "several transducers and corresponding connections [...] integrated into a sweeping or rotating scan head"[5].

2.2.4 LightProbe[8]: The LightProbe is a new concept published in 2019. It gives a prototype for a ultrafast digital probe that allows real-time ultrasound imaging with frame rates of up to 500 fps. The reason for creating this prototype was that although many commercial mobile US probes exist they are still limited when it comes to "ultrafast imaging, vector flow, or elastography [Elastography is a method when using ultrasonography that allows to assess the stiffness of soft tissue and thereby makes it possible to detect cancer[9]]"[8]. Stated is that the main reason mobile devices are not able to do so is that much processing will have to be done on the probe and "digital probes are thermally limited devices"[8]. Fig. 10 shows the probe and its interfaces.

Fig. 10. LightProbe with USB interface for power and control and the optical interface for data[8]

Application
A specific case of application is not given in the paper. But because the probe does satisfy medical safety regulations it can be used in a medical application.

Connectivity
As the LightProbe is equipped with a 64 channel ultrasound front end, somehow the data has to be transfered to the connected device for processing. To get a feeling for the figures heres the calculation led on in the paper. "A 64-channel probe sampling with 12 b at 32.5 MS[Megasamples]/s produces a data stream of 24.96 Gb/s"[8]. Common interfaces like USB 3.1 and 3.2 do not support such high data rates, thus they cannot be used for data transfer.

As a result a optical interface is used that provides a data rate of 40 Gb/s. However the use of a optical interface requires that the back end device, in this case a commodity PC, must be equipped with special hardware.

Processing
As mentioned earlier the probe itself does not process raw data into image data but processes analog into digital data. This is because LightProbe follows a the Software-Defined Architecture, which means that all processing is done in software. This all raw data is sent to the PC via the optical interface. However the developers allowed to add hardware processing blocks to the probe. Beause of the high amount of input data (24.6 Gb/s) a GPU with sufficient processing power must be chosen. The used GPU is the Nvidia Tesla 100 with a processing power of 15 TFLOP/s.

Usability
By using 64-channeled transducer the probe allows a high frame rate of up to 500 fps with a average power consumption of 7.1 W. As a consequence of the high frame rate much power is consumed and thereby much heat is produced. However this probe is able to be used in a medical application which means that the heat must be dissipated quickly thus it does not heat up to over 43°C. Moreover the probe must be disinfected prior usage which cancels out air cooling as a way of thermal management. Therefore the paper introduced a "Dynamic Thermal Management"[8] which regulates the probes temperature using multiple thermal sensors at places where much heat is produced. If the "thermal-aware-performance (TAP) controller"[8] detects too high temperatures the imaging frame rate is reduced to lower power consumption. However "to provide a consistent Qualtity of Service"[8] a Boost-Mode is supported that allows the user to increase frame rate for a specified amount of time (2 s) and "a defined periodocity (every 5 s)"[8].

3 AIM: Acoustic Imaging on a Mobile[2]

While all the previous presented systems used external hardware, this concept uses a Samsung Galaxy S7 and its built-in speaker and microphone. Motivation was that smartphones become more and more powerful and smartphone cameras are getting better. But they still have problems when taking images in the dark or under obstruction. AIM sees its application in security scanning. Thereby it uses the property of acoustic signals, that they can penetrate materials and allow an under clothes weapon detection.

Fig. 11 shows the process of how an image is taken with AIM. When the user starts imaging the phones speaker sends out short periodic acoustic signals, so called chirps, within a frequency of 10 KHz to 22 KHz whereas the microphone records the reflected acoustic signals. To get a complete image the user has to move the phone along a trajectory to mimic a microphone array.

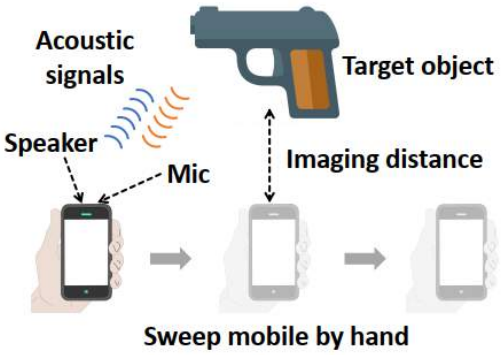
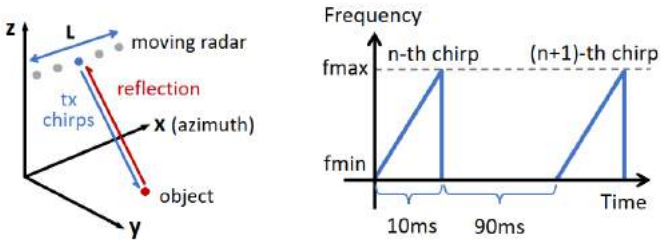


Fig. 11. Process of taking an image with AIM[2]

3.1 Synthetic Aperture Radar (SAR)

The technique on which AIM is based is called Synthetic Aperture Radar (SAR). SAR is used to create radar images of landscapes by simulating a large radar. Fig. 12(a) shows a SAR system, where the radar moves along the azimuth direction denoted. The total distance that is moved by the radar is called synthetic aperture radar, denoted as L. While moving the radar sends out chirps ranging from a minimum frequency to a maximum frequency as can be seen in Fig. 12(b). The time between the chirp signals is long enough that all echoes are received. The received echoes all stored and later used to be put together to an image. Sometimes it can be possible that the radar does not exactly follow the desired azimuth direction. For this case a phase correction algorithm (PGA) is used.



(a) System view (b) Chirp signals

Fig. 12. Synthetic Aperture Radar[2]

3.2 Challenges

One of the main problems is that for a user it is hard to exactly follow the given path and to keep a constant desired speed. To solve this deviation problem the phase correction algorithm of SAR has been improved. Further information about this algorithm can be found in the respective paper. Other problems that are given by the nature of acoustic imaging and the hardware of the phone are "self and background interference"[2] and "speaker and microphone distortion"[2].
Self and background interference occurs when reflection of the background and direct transmission from the speaker itself overlap with the reflected signal of the imaged object.
The *speaker and microphone distortion* is caused by the hardware itself. Because acoustic signals with a frequency above 15 KHz are hardly audible for a human ear, the phones hardware is not optimized for use in this frequency spectrum.
As stated above the deviation problem is solved by the phase correction algorithm. The interference problem is taken care of by having a pre-recorded sound snippet that contains the direct path signals between the microphone and the speaker. These samples are then subtracted from the recorded samples. This cancels out the self interference and leaves the background interference. Background interference is cancelled out in a second stage "by exploiting the fact that it has a different propagation delay from the target reflection"[2]. Now this leaves problem number three: Speaker and microphone distortion. Luckily the distortion affects "the image in a deterministic way"[2], which makes it possible to be cancelled out.

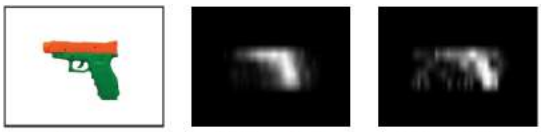


Fig. 13. (a) shows the target object **(b)** shows the image taken with AIM in Line of Sight (LoS) **(c)** shows the same object but now inside a bag[2]

Fig. 13 and Fig. 14 show the target object, an image taken with AIM and a second image taken with AIM with the object inside a black bag.

Fig. 14. (d) shows the target object **(e)** shows the image taken with AIM in Line of Sight (LoS) **(f)** shows the same object but now inside a bag[2]

4 Discussion

Many ultrasound probes exist that allow an in field use with mobile devices. Though a probe provides dedicated hardware for the imaging purpose which allows higher quality because processing can be done in parts on the probe itself and therefore does not need high end back-end processing, it is still an additional device that must be carried around to come to use. For this reason the approach of AIM is really promising. With further improvements done, one day it might be possible to use a smartphone to make an first aid organ scan after an accident to see if a victim has internal bleeding.
The most powerful of the presented probes seems to be LightProbe. However it uses advanced technology that is not yet available for commodity mobile devices, thus further hardware improvements are necessary to support the high requirements of LightProbe. To be able to support LightProbe a smartphone would need an optical or high speed interface for data transmission and a high performance GPU. All this would lead to a high power consumption what makes it unlikely that LightProbe will ever be compatible with a smartphone.
The open hardware approach is a good source for tinkerers and enthusiasts who like to experience low level ultrasound imaging. For further usage the hardware is limited, yet alone because a single channel transducer is used what makes the use of a servo motor (or the like) necessary. Furthermore a single channel does not provide the same resolution and frame rate that might be needed. This and the modular approach, which is good for the sake of simplicity and flexibility when it comes to hardware choices, increases the size and volume of the whole system.
The probe introduced in sections 2.2.1 and 2.2.2 shows that ultrasound imaging is possible with a decent quality on commodity smartphones. With todays high-end smartphones an even more powerful probe would be able to be made. This would allow serious usage in health care applications.
AIM seems to be the state of the art solution when it comes to imaging without external hardware. However it is limited in its quality because the hardware of smartphones is not optimized for this kind of usage. Maybe with optimized hardware for the required bandwidth of AIM a better imaging quality could be achieved. When improving this hardware it might also be interesting think about increasing the spectrum of the speaker and microphone. Furthermore the

process of taking an image with AIM is quite complex compared to taking a camera image. This should be improved if AIM is to be seriously used.

5 Conclusion

This paper has shown that object imaging has various advantages against common camera imaging. It has shown as well that smartphones are already powerful enough to perfrom image processing of acoustic signals. Many approaches exist for US imaging supported by a smartphone that allows usage in medical applications. The external hardware for US imaging can also be used to improve the imaging quality but is limited by the interfaces of smartphones.

Not only can images be taken with external hardware but also with built-in hardware only. AIM has helped to see how such an approach can look like. Although the imaging quality is limited it became visible that with improved hardware the imaging quality can be improved as well.

References

1. H. Bedri, M. Feigin, M. Everett, G. L. Charvat, R. Raskar, *et al.*, "Seeing around corners with a mobile phone?: synthetic aperture audio imaging," in *ACM SIGGRAPH 2014 Posters*, p. 84, ACM, 2014.
2. W. Mao, M. Wang, and L. Qiu, "Aim: Acoustic imaging on a mobile," in *Proceedings of the 16th Annual International Conference on Mobile Systems, Applications, and Services*, MobiSys '18, (New York, NY, USA), pp. 468–481, ACM, 2018.
3. S. Ahn, J. Kang, P. Kim, G. Lee, E. Jeong, W. Jung, M. Park, and T.-k. Song, "Smartphone-based portable ultrasound imaging system: Prototype implementation and evaluation," in *2015 IEEE International Ultrasonics Symposium (IUS)*, pp. 1–4, IEEE, 2015.
4. E. Jeong, Sua Bae, M. Park, W. Jung, J. Kang, and T. Song, "Color doppler imaging on a smartphone-based portable us system: Preliminary study," in *2015 IEEE International Ultrasonics Symposium (IUS)*, pp. 1–4, Oct 2015.
5. L. Jonveaux, "Arduino-like development kit for single-element ultrasound imaging," *Journal of Open Hardware*, vol. 1, no. 1, 2017.
6. H. S. P. Explained, "ultrasound - b scan explained." `https://www.youtube.com/watch?v=Tg_KJ0XqnJ8`, 2016. Accessed on 05-07-2019.
7. T. Binder and M. Altersberger, "1.8.2.1 principles of color doppler." `https://www.123sonography.com/ebook/principles-color-doppler`, 2019. Accessed on 05-07-2019.
8. P. A. Hager and L. Benini, "Lightprobe: A digital ultrasound probe for software-defined ultrafast imaging," *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 2019.
9. S. M. Dictionary, "elastography." `https://medical-dictionary.thefreedictionary.com/elastography`, 2012. Accessed on 06-07-2019.

Vergleich Verschiedener Architekturen künstlicher Intelligenz

Denis Jager

Karlsruher Institut für Technologie

Abstract. In dieser Ausarbeitung sollen verschiedene Architekturen künstlicher Intelligenz nach ihren Anforderungen und Entscheidungsdimensionen verglichen werden. Die Architekturen künstlicher Intelligenz lassen sich in überwachtes Lernen, unüberwachtes Lernen und bestärkendes Lernen unterteilen.

Table of Contents

1 Forschungsfrage

In Zukunft sollen KIs immer automatisierter entworfen und genutzt werden. Dazu ist es wichtig zu wissen welche Architektur künstlicher Intelligenz bei dem jeweiligen Problem angewendet werden soll. Um dies zu erreichen werden in diesem Paper einige der wichtigsten Architekturen künstlicher Intelligenz anhand ihrer Anwendungsgebiete, Vorteile und Nachteile aufgeführt.

2 Überwachtes Lernen

Es werden nun einige Grundlagen zu überwachtem Lernen angeführt. Daraufhin sollen verschiedene Architekturen dieser Kategorie anhand ihrer Anwendungsgebiete, Vorteile und Nachteile aufgezählt werden.

Trainingsdaten: Beim Überwachten Lernen beinhaltet jedes Trainingsbeispiel einen oder mehrere Inputs und einen gewünschten, zugehörigen Output.

Vorgehen: Durch die iterative Optimierung einer Zielfunktion lernen überwachte Lernalgorithmen gewünschte Outputs für neue Inputs vorherzusagen.

Kategorien Wenn die Outputs in diskrete Werte unterteilt werden können handelt es sich um eine Klassifikation. Bei der Regression ist keine Einteilung zu diskreten Werten möglich. Die Outputs sind hier kontinuierliche Werte.

2.1 Recurrent Neural Networks (RNN)

Anwendungen:

1. Spracherkennung [4]
2. Schreibschrifterkennung [4]

Vorteile:

1. Starkes Modell für die Verarbeitung sequenzieller Datenströme [4]
2. Größerer Zustandsraum und dynamischer als hidden Markov models [4]

Nachteile:

1. Potenziell falsche Ausrichtung als Trainingsziel [4]

2.2 Convolutional Neural Networks (CNN)

Anwendungen:

1. Klassifikation von Bildern [2]

4

Vorteile:

1. Effektiv für das Verarbeiten riesiger Datensätze [2]

Nachteile:

1. Es werden riesige Datensätze benötigt [2]

2.3 Random Forests

Anwendungen:

1. Genetik [13]
2. Medizin [13]
3. Bioinformatik [13]

Vorteile:

1. Guter Umgang mit Rauschen im Merkmalsraum [8]
2. Guter Umgang im Falle vieler Prediktor Variablen [13]
3. Guter Umgang mit hochdimensionalen Probleme [13]
4. Können sowohl für Klassifikation als auch für Regression genutzt werden [13]

Nachteile:

1. Eigenschaften sind schwerer vorherzusagen als bei anderen parametrischen Methoden [13]

2.4 Decision Trees

Anwendungen:

1. Diagnose in der Medizin anhand von Symptomen [11]
2. Verschiedene Klassifikationsaufgaben [11]

Vorteile:

1. Lernmethoden sind weniger komplex als bei anderen Architekturen [11]

Nachteile:

1. Rauschen in den Trainingsdaten verursachen ungenaue Attribute oder führen zu einer falschen Komplexität des Decision Trees [11]

2.5 Boosted Decision Trees

Anwendungen:

1. Partikel Identifikation in der Physik [12]
2. Datenklassifikation [12]

Vorteile:

1. Starke Lernmethode mit hoher Performanz [12]
2. Effizient bei hoher Attributanzahl [12]

Nachteile:

1. Kleine Änderungen in den Trainingsdaten können zu großen Änderungen im Baum und in den Ergebnissen führen [12]

2.6 Gradient Boosting

Anwendungen:

1. Reisezeit Prognosen [15]

Vorteile:

1. Weniger sensitiv gegenüber einer erhöhten Vorhersagemenge als andere Modelle [15]
2. Gute Vorhersageperformanz und Vorhersagegenauigkeit [15]

Nachteile:

1. Performanz ist stark von den Parametern des Modells beeinflusst [15]

2.7 Support Vector Machine (SVM)

Anwendungen:

1. Text Kategorisierung [7]

Vorteile:

1. Vollautomatisch, das heißt keine manuelle Parameter Einstellung nötig [7]
2. Guter Umgang mit hochdimensionalen Inputs [7]
3. Robust [7]

6

2.8 Naive Bayes

Anwendungen:

1. Text Klassifikation [10]

Vorteile:

1. Parameter für jedes Attribut können separat gelernt werden, wodurch das Lernen vor allem für eine große Zahl an Attributen vereinfacht wird [10]

3 Unüberwachtes Lernen

Es werden nun einige Grundlagen zu unüberwachtem Lernen angeführt. Daraufhin sollen verschiedene Architekturen dieser Kategorie anhand ihrer Anwendungsgebiete, Vorteile und Nachteile aufgezählt werden.

Trainingsdaten: Beim Unüberwachten Lernen beinhaltet jedes Trainingsbeispiel einen oder mehrere Inputs. Im Gegensatz zum Überwachten Lernen fehlen die zugehörigen, gewünschten Outputs.

Vorgehen: Vom Algorithmus sollen selbstständig Strukturen in den Daten gefunden werden, wie zum Beispiel Ähnlichkeiten zwischen mehreren Trainingsbeispielen. Neue Inputs können dann auf Anwesenheit einer solchen Ähnlichkeit überprüft werden. Der Algorithmus verfährt dann entsprechend.

3.1 K-Means

Anwendungen:

1. Clustering

Vorteile:

1. Einfach zu implementieren

Nachteile:

1. Es ist schwer den Wert für K zu bestimmten [3]
2. Nicht effektiv bei globalem Cluster [3]
3. Bei unterschiedlichen Startpartitionen kann auch das Ergebnis sich verändern [3]

3.2 Hierarchical Clustering

Anwendungen:

1. Fehlende Strukturen in einem großen Datenarray finden [1]
2. Psychologie [1]

Vorteile:

1. Schnell in der Berechnung [1]
2. Invariant bei gleichbleibender Transformation der Daten [1]
3. Kann Cluster finden die optimal "verbunden" sind oder optimal "kompakt" [1]

3.3 Deep Belief Networks

Anwendungen:

1. Visuelle Wiedererkennung [6]
2. Erkennung handschriftlicher Zahlen [6]
3. Motion Capture [6]

Nachteile:

1. Es ist schwer solche Modelle für hochdimensionale Probleme zu skalieren [6]

4 Bestärkendes Lernen

Es werden nun einige Grundlagen zu bestärkendem Lernen angeführt. Daraufhin sollen verschiedene Architekturen dieser Kategorie anhand ihrer Anwendungsgebiete, Vorteile und Nachteile aufgezählt werden.

Vorgehen Bestärkende Lernalgorithmen legen fest wie Software Agenten in einer bestimmten Umgebung agieren sollen. Dazu wird eine positive Rückmeldung benutzt, falls er sich richtig verhalten hat. Durch diese positive oder bestärkende Rückmeldung wird nach und nach gelernt wie ein korrektes Verhalten aussieht.

Anwendungen Im Folgenden werden einige Anwendungsgebiete für das bestärkende Lernen aufgelistet.

1. Autonomes Fahren
2. Lernen des Spielens gegen einen menschlichen Gegner

8

4.1 Q-Learning

Anwendungen:

1. Web System Konfiguration
2. Nichtmenschlicher Spieler in Spielen [5]

Vorteile:

1. Einfacher Weg für Agenten das optimale Handeln in kontrollierten Markov Umgebungen zu lernen [14]

Nachteile:

1. Überschätzen von Aktionswerten unter bestimmten Bedingungen [5]

4.2 Deep Q-Networks

Anwendungen:

1. Autonomes Fahren [9]
2. Nichtmenschlicher Spieler [9]

Vorteile:

1. Gut für Probleme mit hochdimensionalem Überwachungsraum [9]
2. Kann bei vielen Aufgaben die Strategien auch "end-to-end" lernen [9]

Nachteile:

1. Kann nur mit diskreten und niedrigdimensionalen Aktionsräumen umgehen [9]

4.3 Deep Deterministic Policy Gradient

Anwendungen:

1. Nichtmenschlicher Spieler [9]

Vorteile:

1. Kann kompetitive Strategien für alle Aufgaben lernen [9]

Nachteile:

1. Instabil bei anspruchsvollen Problemen [9]

References

1. Administrator. 241_1.tif.
2. Alex Krizhevsky, Ilya Sutskever, and Geoffrey E. Hinton. Imagenet classification with deep convolutional neural networks.
3. Preeti Arora, Deepali, and Shipra Varshney. Analysis of k-means and k-medoids algorithm for big data. *Procedia Computer Science*, 78:507–512, 2016.
4. Alex Graves, Abdel-rahman Mohamed, and Geoffrey Hinton. Speech recognition with deep recurrent neural networks. In *2013 IEEE International Conference on Acoustics, Speech and Signal Processing*, pages 6645–6649. IEEE, 26.05.2013 - 31.05.2013.
5. Hado van Hasselt, Arthur Guez, David Silver. Deep reinforcement learning with double q-learning.
6. Honglak Lee, Roger Grosse, Rajesh Ranganath, and Andrew Y. Ng. Convolutional deep belief networks for scalable unsupervised learning of hierarchical representations.
7. Thorsten Joachims. Text categorization with support vector machines: Learning with many relevant features.
8. Christopher Krauss, Xuan Anh Do, and Nicolas Huck. Deep neural networks, gradient-boosted trees, random forests: Statistical arbitrage on the s&p 500. *European Journal of Operational Research*, 259(2):689–702, 2017.
9. Timothy P. Lillicrap, Jonathan J. Hunt, Alexander Pritzel, Nicolas Heess, Tom Erez, Yuval Tassa, David Silver, and Daan Wierstra. Continuous control with deep reinforcement learning.
10. Andrew McCallum and Kamal Nigam. A comparison of event models for naive bayes text classification.
11. J. R. Quinlan. Induction of decision trees.
12. Byron P. Roe, Hai-Jun Yang, Ji Zhu, Yong Liu, Ion Stancu, and Gordon McGregor. Boosted decision trees as an alternative to artificial neural networks for particle identification. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 543(2-3):577–584, 2005.
13. Carolin Strobl, James Malley, and Gerhard Tutz. An introduction to recursive partitioning: rationale, application, and characteristics of classification and regression trees, bagging, and random forests. *Psychological methods*, 14(4):323–348, 2009.
14. Christopher J.C.H. Watkins and Peter Dayan. Q-learning.
15. Yanru Zhang and Ali Haghani. A gradient boosting method to improve travel time prediction. *Transportation Research Part C: Emerging Technologies*, 58:308–324, 2015.

Edge Computing - An overview of a cloud extending technology

Evgeni Cholakov
ugtye@kit.edu

Karlsruher Institut für Technologie

Abstract. Cloud computing is a powerful technology which has proven itself through the years, but it is demanding in price. Moreover, with the rising number of Internet of Thing devices, a time is coming in which cloud computing will not be able to cope with the amount of data to process and, what is more, it use leads to high internet traffic congestions. Fog computing was the first extension of cloud computing presented in order to cope with the disadvantages of cloud computing. Physically extending the cloud showed great results, but still the option remained to go even further, closer to the end user. Therefore, we introduce edge computing as an extension of the cloud computing technology which aims to offload the cloud and bring the computing of data closer to the end devices, which all together form the edge of the network.One of its greatest advantages is the fact that the concept is based on already developed technologies such as Software Defined Networks and Network Function Virtualization. Edge computing reveals itself as a technology from which the cloud and the network could benefit. It is able to accelerate network services while reducing the internet traffic. It assists in providing faster and better services for the Internet of Things devices and it is a crucial step in the realisation of the 5G network. The following paper presents an overview of this new and emerging concept.

1 Introduction

1.1 Motivation

Cloud computing is an idea which can be traced back to the early 60s of the last century. In the 90s we came closer to making the idea possible by introducing VPN. Traffic was switched in a way so it would improve the overall use of the internet bandwidth.It was the 2000s when the cloud as we know it today was brought to life.[4] The technology of cloud computing brought with itself not only technological but also business advantages for the customers. Buying your own hardware is an expensive investment which is profitable if only the full computing capacity of the system is used. Most of the businesses, especially the small ones, hardly ever achieve this. Therefore, paying only for the used services is a smarter idea.[5] Furthermore, cloud computing offers the possibility for software and data to be accessed easily by different kinds of client devices

2

and no matter the location, as long as there is an internet connection.[11] Given these advantages, cloud computing has established itself as one of the leading technologies in the IT sector.
Although its great success, cloud computing has its drawbacks, which are creating the need for a new solution. Fact is that great quantities of data and software are stored in a cloud and need to be accessible at all times. This leads to the requirement of the cloud to be available all of the time. Cloud outages occur frequently and can be crucial. Moreover, always-on requirement results in great costs. On the business side of the idea there is a small number of major suppliers on the market. This leads to little competition between suppliers and high costs of the service. This obstructs small enterprises from joining the cloud.[11]
Furthermore, a concept called Internet of Things (IoT) is creating even greater challenge for the cloud computing. The main idea of the IoT is the vast presence of devices around us which are collecting data and are sending it to the cloud.[2] [10] This means that great amount of data first needs to be sent to the cloud, processed there, stored and, on request, sent again to the requesting device. This whole process results in high traffic and processing costs. According to Cisco Global Cloud Index, 847 ZB of data will be generated by devices per year by 2021.[3] All of this activity could lead to exhausting the cloud resources and hence lower quality of service.

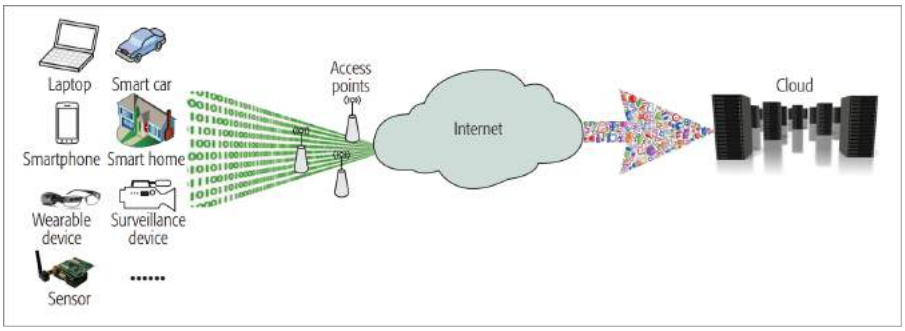


Fig. 1: Traditional Cloud with Internet of things architecture [12]

Imagine if there was a way to accelerate the whole process of collecting and utilizing data. A technology which could greatly reduce the response time of a service and at the same time take some pressure of the internet traffic. And all of this done without introducing new and complex hardware but the opposite by extending the idea of cloud computing and utilizing the present resources. Today we are closer to this achievement by introducing edge computing.The idea of edge computing has actually been around for quite some time but, because of the great success of cloud computing until today, it has not received the needed attention. In the article we will discuss the main idea of edge computing followed

by the technologies which help the realization of edge computing and present possible integration in the mobile networks. A section on the advantages which come with it is presented as well as the possible applications. Lastly, we will take some time to discuss the challenges which the idea is facing.

1.2 What is Edge Computing

Edge Computing presents the idea of doing the processing task of data near the devices which produces it instead of sending it all the way to the cloud. Edge computing consists of edge nodes which are able to fulfil request. An edge node is every device which is standing on the way between a data generating device and the cloud. An example of an edge node could be a small server in a smart home which collects data from all of the present sensors or even our own smartphone or smartwatch.[10] [14] Furthermore, edge computing could be used in the mobile technologies where it is known as Mobile Edge Computing.

1.3 Mobile Edge Computing

Edge computing is recognized by the European 5G Infrastructure Public Private Partnership (5G PPP - an organisation, responsible for delivering solutions, standards, architectures and technologies for the next generation mobile communication) as a key technology towards 5G. [6] Therefore, edge computing is tightly connected to the mobile networks. Mobile Edge Computing (MEC) is the integration of the concept of Edge Computing inside the mobile network. The idea is to move the data processing in Radio Access Network and thus get closer to the mobile subscribers.[6] Mobile Edge Computing implements the 3 levels architecture which is described in a more detailed way in the next subsection. End devices may perform small computation tasks as well as communicate with MEC servers. MEC servers can be stationed inside radio towers or even closer to the user. Base stations and mobile access points in public places can be utilized as MEC servers. With the help of the mobile network those servers are again connected with the cloud which represents the third level of the architecture.[1]

1.4 Edge Computing Architecture

The architecture of edge computing is based on the idea of bringing the processing task closer to the end user. Thus providing better quality of service. Very important role in integrating edge computing have the edge computation nodes. These are also known as edge/cloudlet servers. In the basic concept of the edge computing architecture we can distinguish 3 levels of computing nodes. The first one is the closest to the end user. It consist purely of the devices which generate the data. By interacting with this level the user experiences the lowest latency and the best quality of service. Data needs to travel smaller distances or not any at all in order to be processed.On the other hand devices in the first level do not have much computing power in order to respond to difficult request or handle

great amount of data. For this reason there is a second level in the architecture. This level consists of edge computing servers or cloudlet servers. The second level of the architecture represents the main core for the most of the data processing and storing in the era of edge computing. Those servers have more computing capacity than the devices in level 1 and are able to fulfil the request involving heavy data processing. Still the nodes on this level are not capable of heavy parallel processing or running tasks which involve big data. Therefore, there is a third level in the architecture. This level is actually the well known cloud. It is deployed on a great distance from the end user and has the same drawbacks as the today's cloud computing. However it is able to compensate for lack of ability of level 2 to handle the most difficult data processing tasks.[14]

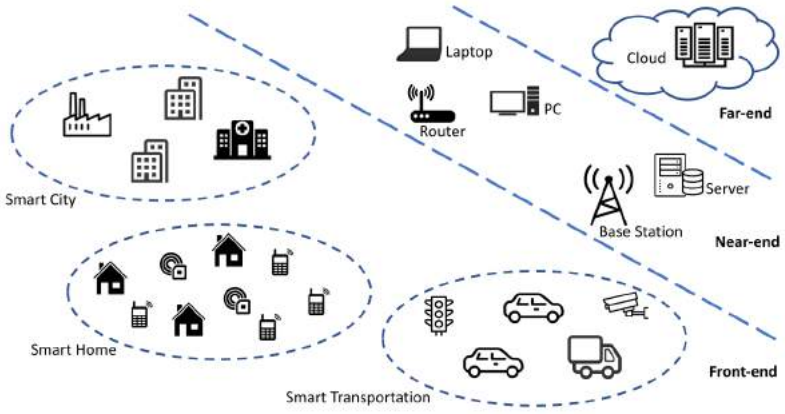


Fig. 2: Edge Computing Architecture [14]

1.5 Fog Computing vs. Edge Computing

Fog computing is another idea of improving data processing which is often being mistaken for Edge Computing. There is a slight difference. The idea of fog computing is to extend the cloud with smaller clouds/fog nodes and physically move them closer to the user. By doing this the processing is distributed amongst multiple clouds, while decreasing latency as well as increase quality of service. The variety of devices which can be classified as a fog node is wide. Any device with storage and computing capacity could be identified as a fog node. Given those facts we can conclude that fog computing is more about the infrastructure. It is about how efficient distributed clouds/fog nodes are located in the network in order to reduce the traffic load.[13]

2 Enabling technologies

In order to make the idea of edge computing reality we need to examine and use some of the already developed technologies in the networking sector. In the following sections we are going to look in the technologies which are assisting the realisation of edge computing. Edge computing relies not only on cloud computing but also on technologies such as Network Function Virtualization (NFV), Software Defined Networks (SDN) and network slicing.

2.1 Network Function Virtualization

Network Function Virtualization is a technology in the networking which is used in order to provide multi-tenancy servers, which are located closer to the user. Earlier, every content provider had to use its own hardware in order to provide service to its users. Different hardware systems mean that it is harder to standardise services. Failures and errors are difficult to fix. The greatest drawback was that, to relocate a service, the content providers needed physically to relocate the server or order a new one. NFV enables a single server to be used by different content providers. The idea is to have a single hardware which has is own operating system and uses virtualization in order to provide hardware resources to different services. Content providers only need to provide a functioning software. To sum up NFV provides easier migration, flexibility and scalability.[15]
For example in the case of a flash crowd event the resources of an edge computing server might be exhausted. By using the technology of NFV the server may allocate additional resources on another near edge computing server without concerning compatibility.[13]

2.2 Software Defined Networks

Software Defined Networks are another networking technology which is recognised as the future of networking. By SDN there is a strong separation between data and control layer. The traditional model of a router has both layers integrated. This means that a routers makes its own routing decision based on data which is sent to it. In the SDN the routers are replaced with simple switches which only switch packets. The control functions are placed in a single controller which makes the routing decisions and sends them in form of rules to the switches. The switches save those rules in tables and when they receive a packet they switch it, based on the rules in their tables. SDNs provide centralized control of the network. Flexibility is provided and the whole network can be easily adjusted. This means that new network services can be also easily added.SDN provides an agile and easy to manage connectivity which can span across many servers and devices at the edge of the network.[13] [15]

6

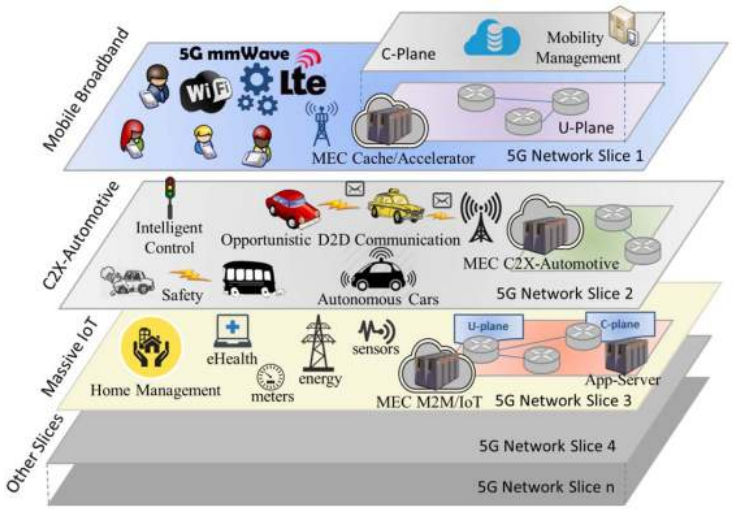


Fig. 3: Different network slices for a single network [13]

2.3 Network Slicing

Network slicing is the next key element in bringing the idea of edge computing to life.It is the technology of being able to divide a network in smaller networks which fulfil different requirements. By combining the technologies of SDN and NFV we can divide a single physical network into smaller virtual instances which are dedicated to a single service or application. Thus providing easier control over the service/application and greater customization. Therefore, by using network slicing, we can customize the whole edge computing infrastructure into different network slices such as Mobile Broadband slice, Automotive slice or Massive IoT slice and provide each of these slices only with their needed network resources and functioning rules. By using this separation of services we have a tighter control over the network and at the same time we are able to change and improve services in a more flexible way. [13]

3 Edge Computing Integration in Mobile Networks

In the following section we are going to look at some possible integrations of edge computing in the present mobile network. We try to integrate edge computing by extending the capabilities of the present devices in the mobile network.

3.1 Small Cell Cloud

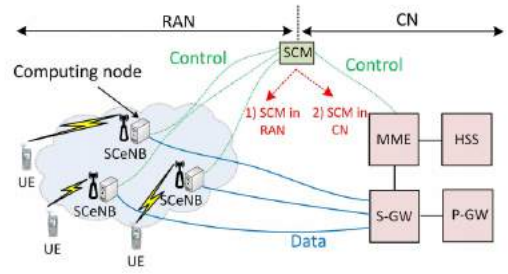
First we take a look at the model which performs the computing in a really close proximity to the end device. The small cell model utilizes the small cells in a mobile network, which are shown in figure 4.

Two femtocells inside a home

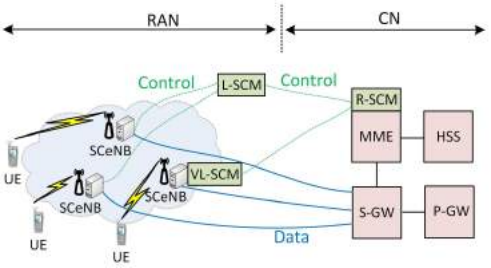
Small cell on the street

Small cell on a building

Fig. 5: Examples of different types of small cells [4]



a) Single SCM



b) Distributed SCM

Fig. 7: The two possible integrations using small cell cloud [7]

In the model we attach an additional device which is responsible for processing data. The device could be a simple computer. Then we can form a cloud by clustering together a number of small cells which are closer to each other. In order to achieve this model we need to include also an additional controller (SCM - small cell controller). This controller is responsible for distributing task across the small cells in a small cell cloud. Furthermore, small cell are frequently being turned off or are being disconnected from the network. The small cell controller

is responsible for handling the loss of a small cell in such event. There are two possible ways to include the SCM in the model. The first is the single SCM, which is located near a cloud of small cells (a)). The second option is to have a distributed control over the clouds (b)). We have a local SCM (L-SCM) or a virtual SCM (VL-SCM), located on a small cell, which is taking the responsibilities of a manager for the local cloud. Then we have a remote SCM (R-SCM), which is located in the core network and has information about all of the small cells, connected to the core network.[7]

3.2 Mobile Micro Cloud

Secondly we are going to discuss the Mobile Micro Cloud (MMC). Here the computation of data happens a little bit further from the end device but still near the edge of the network. The data processing task is performed at the base station towers (eNB). Each of the towers is provided with a computing entity, responsible for handling processing and storing tasks. Computing entities are allowed to communicate with each other in order to form a cloud-like system at the edge of the network as well as ensure that the end device would receive constantly good service while moving through the network. Different from the

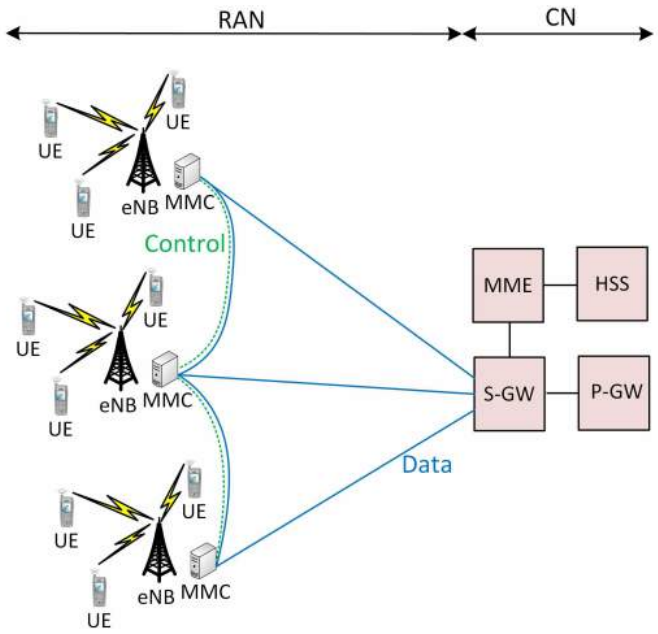


Fig. 8: Mobile Micro Cloud model [7]

SCC model is the fact that by the MMC model we do not have a separate controller entity. The control is performed in a distributed manner, similar to the VL-SCM in a SCC model.

3.3 Fast Moving Personal Cloud (MobiScud)

Now we take a look at the third possible integration of edge computing in mobile networks - the fast moving personal cloud, which is also known as MobiScud model. The model differs from the last two presented mainly by the position of the computing devices in the architecture. In SCC and MMC we used an additional hardware which was located at access points.Here the data processing and storing task happen in small clouds which are located in the radio access network. The clouds are accessed by the devices through a software defined network. In this model we need to include a controller for each cloud and its SDN, called MobiScud Controller (MC). Its main tasks are monitoring the activity of end devices by examining control plane massages exchanged between elements in the mobile network as well as creating and distributing rules across the switches in a SDN. [7]

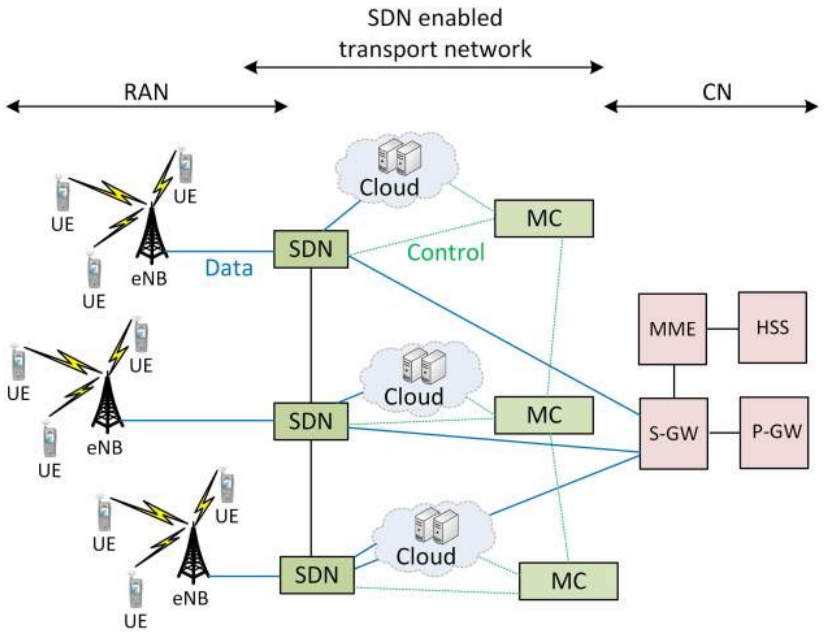


Fig. 9: Fast Moving Personal Cloud model (MobiScud) [7]

10

3.4 FollowMe Cloud

Last but not least we are going to look into the FolloMe Cloud model. It is based on the idea that mobile network providers will need to divide their core network into subnetworks in order to cope with the growing number of end devices. This could be achieved through the technology of network slicing. In the FollowMe Cloud we have a distributed cloud system, which provides a separate cloud (Distributed Cloud - DC) for each network slice. Additionally we need to include two new entities which assist in managing the whole architecture. We include a mapping entity (DC/GW Mapping entity), responsible for initializing connection between a network slice and a DC. Then we have the FollowMe Cloud Controller (FMCC), which manages the storage and processing resources of a DC. [7]

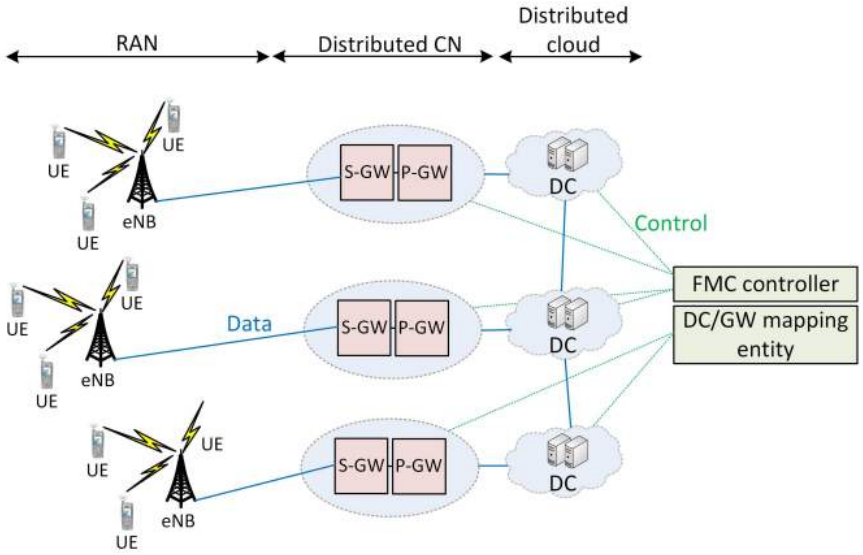


Fig. 10: FollowMe Cloud model [7]

4 Advantages of Edge Computing

In the following section are presented and discussed the advantages of edge computing. We pay attention to the problems which cloud computing is facing and provide a solution in the face of edge computing by discussing how its advantages assist in improving the user experience.

4.1 Responsiveness

The time which an application or service takes to accomplish a task, also known as response time or responsiveness, is crucial for today's quality of service. It is known that the average user keeps his attention on a task for no more than 10 seconds. Anything slower than that leads to worse user experience.[9] Furthermore, there are numerous technologies which are time-sensitive. This means that they require very short response time in order to function properly and provide good services. Edge computing could achieve those result and satisfy the low response time demand by utilizing the computing capacity of the edge devices. Combined with an algorithm which prioritizes tasks and decides which to be performed locally and which to be sent to a near edge computing server, it could be a step towards faster responsiveness.[14]
To prove its ability to perform crucial tasks faster there is a face recognition platform developed which utilizes the edge nodes rather than the cloud. The result show that a task is performed for a total of 169 ms rather than 900 ms which were needed by the platform if it was using the cloud for computation. Moreover, by wearable assistance devices, the response time is reduced from 80 ms to 200 ms by using the technology of the edge computing.[10]

4.2 Internet traffic

Driven by the growing number of IoT devices, the internet traffic has increased significantly in the recent years. More and more devices generate data and need computation capacity in order to process it. This capacity is provided by the cloud but when all of the devices transmit packages to the cloud the internet traffic becomes congested which could lead to great delays and packet losses.Edge computing reveals a solution to this problem by distributing the computing capacity in edge servers physically located on key locations. Data from different devices does not need to travel large distance and also to the same server. Moreover, by using the computing power of the data generating device, some tasks can be performed locally and thus not cause any traffic at all.[8] [14]

4.3 Power consumption

Always sending and receiving data requires for the Wifi interface of the device to be always functioning. This is an activity which requires a lot of power due to the high energy demand of the Wifi interface. IoT devices have very limited power at disposal. Therefore, it is crucial for the devices to save it. Moreover, when the traffic in the network is increased, the congestions can cause a need for the device to use, for a long period of time, its internet interface. Therefore, a lot of power will be wasted. Edge computing provides the opportunity for the devices to transmit data for a shorter period of time or not at all. Hence the power consumption will be reduced.[14] [10]

12

4.4 Storage

The edge computing concept provides a distributed storage system. This means that data could be stored across different physical devices at the edge of the network and not in a centralized cloud system. This method of storing data could lead to lower storage requirements for the cloud, lower pressure on the cloud and hence could result in a drop of the prices of the storage service of the cloud. Furthermore, a great advantage of the edge computing is its ability to enable the technology of data replication. Because it is a distributed system, data will be divided and stored in fixed blocks on different devices. Those blocks overlap and give us the opportunity to restore lost blocks of data by using other ones from neighbouring edge severs. Moreover, by edge computing the devices which store the data can be physically located at different places. This provides the ability to replicate data and store it at different locations. By doing this the danger of loosing data could be significantly decreased.[14] [8]

5 Application of Edge Computing

In the following section we will discuss some of the applications of edge computing. Scenarios will be presented in which edge computing plays a significant role and helps in providing a better service.

5.1 Surveillance Cameras

One of the most famous possible application of edge computing is by collecting data from surveillance cameras. This example provides a simple and clear view of the possibilities of edge computing. In a scenario where we have a missing person, one way of finding them is by processing the records of video cameras. But in an urban environment, where there is a huge number of cameras, also a huge number of data needs to be processed. It is a really heavy task if all of the cameras need to send their data to the cloud. Also, the processing would take a lot of time and slow down the search. Time is really important in those situations. By using edge computing the cloud is relieved from this huge pressure and time can be reduced. The cloud only needs to produce the request and then send it to the devices. Each of the devices performs its own processing of its own data and only needs to report the results to the cloud. A lot of traffic costs can be saved as well as processing time can be reduced.[10] [14]

5.2 Smart Environment

One of the ideas which have gained a huge popularity lately is the idea of smart environment. In the following subsections we divide the idea in some of its basic components.

Smart Grid An idea which is being discussed lately is the idea of smart grid. Smart grid is being called the next generation of power grid. But in order to be achieved a lot of sensors, meters and other tracking devices need to be used. They need to be able to communicate fast and their data should be efficiently collected and processed. Here the concept of edge computing appears to be one of the enabling technologies for smart grid.

Smart Home Other technology assisted by the edge computing is the smart home. An average household nowadays consists of many appliances and electronic devices. Each of these technologies is equipped with numbers of sensors and trackers. In order to provide the user with rich and useful information as well as an easy control over the home, all of the data from these devices needs to be processed efficiently. Moreover, this data is only relevant for the current home and therefore there is no point in processing it in the cloud. Imagine if every smart home, which generates tons of data, sends it to the cloud for processing. Huge network congestions as well as high pressured will be the results. By providing and edge gateway and using an edge operating system we can enable data to be collected and processed locally and thus relieve the network and cloud from a great pressure. Furthermore, the quality of the user experience could be strongly increased.[10]

Smart Transportation Autonomous driving is one of the researched technologies nowadays. In order to control and coordinate a large number of vehicles a lot of information from different sensors needs to be processed in a vehicle to vehicle network. In this use case the delay is crucial, therefore fast data transmitting and processing is required. Edge computing could satisfy those requirements of smart transportation. There is currently proposed infrastructure-based vehicle control system by Sasaki. By enabling source sharing between edge and cloud servers the latency is significantly decreased.[14]

Smart City By combining huge numbers of smart homes and the other mentioned smart technologies we can expand to a smart city. In a smart city there would a vast number of sensors without counting the ones which would be used in the previously mentioned technologies. A smart city would generated PBs of information per day which could strongly affect the network transport and cloud capacity in a bad way. Furthermore, for cases which involve emergency or public safety, time is really important and delay should be minimized. We have already discussed the ability of edge computing to tackle those problems, therefore it is one of the main steps towards achieving a smart city.[10]

5.3 Content delivery and network acceleration

Network content which is accessed by users is stored on the servers of the content providers. When requested the request is handled by those servers. When the

server needs to respond to multiple requests, users may experience interruptions or low quality of service. Moreover, because of the geographical location of the server, the data may need to travel long distances. Edge computing servers could help in improving content delivery. Edge computing server can collect data and create statistics about popular content for their region. Then this content can be pre-fetched and the user requests can be handled at those edge computing servers. Furthermore, edge computing introduces the ability of hybrid fetching. When content is missing from the edge server it is not necessary for the request to be sent to the server of the content provider. Data could be requested from other nearby edge servers.[1]
Edge computing servers can be used to track and collect data about the network

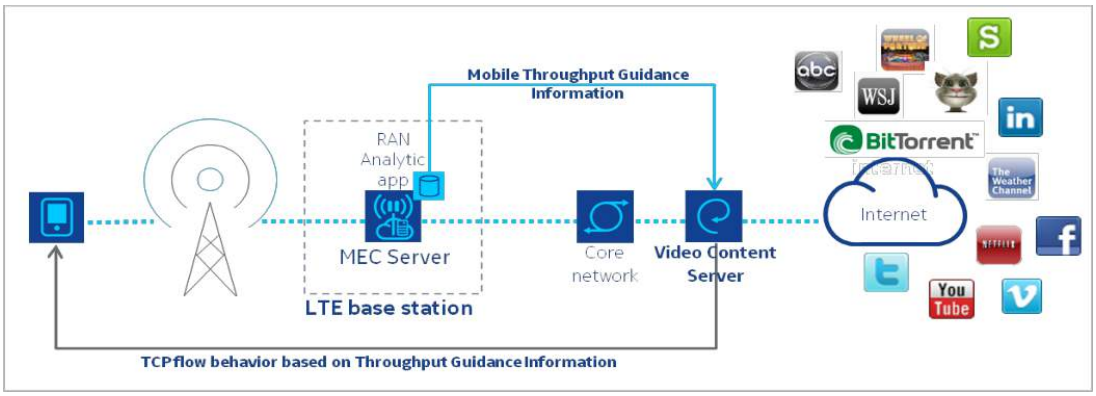


Fig. 11: Using MEC Server to detect network usage and provide statistics to provider, which is used to adjust network settings. [6]

in their region. This data could include number of users per time period, network speed, network pressure. Then this information could be provided to content delivery servers in order to help them establish a faster connection. This data could help by the decision concerning for example the congestion window in a TCP connection. Even more practical example is the streaming of a video. The video provider could use the data from an edge computing server in order to optimize the video experience for all of the users who are currently watching.[6]

5.4 Augmented Reality

Augmented reality is the idea of combining real and virtual world. For example, when visiting a museum or simply taking a walk through a city, a user can turn his phone to a point of interest and with the help of an application and internet they could obtain information about the point of interest on their device. In the current example different sensors such as camera and GPS tracker are combined to collect data which is then processed and the user is provided with

a response. In the case of augmented reality low latency and fast processing are crucial for the realisation of the idea. Therefore, edge computing proves itself as an excellent technology for the case. Data could be sent to and processed in MEC servers closer to the desired point of interest rather than in a distant cloud server. The response time gets faster and the network is not additionally loaded. Moreover, this data is irrelevant for anything else outside of the zone of the point of interest.[6] [1]
Examples for augmented reality are Google Goggles, Layar, Junaio. Brian Computer Interaction is another example for AR which utilizes the power of edge computing. The idea is to detect human brainwaves with the help of a headset and a phone. Then data is sent to a mobile edge server where it is processed. Communication with the cloud could also be used but only for archiving purposes.[1]

6 Challenges of Edge Computing

We already discussed what are the advantages of the edge computing and how it could improve the overall performance of network services. We have also given examples for possible applications. But it since it is still a new technology which is being developed there are challenges which are still to be tackled. In the following section we will discuss some of the problems which edge computing is facing and give examples of ideas which could help in solving them.

6.1 Programmability and Integration

In the centre of the idea of edge computing is the combination and utilization of various physical devices and different network topologies. This means that applications and services need to be able to cope with different platforms and resources. By cloud computing the infrastructure is transparent to the user. They do not know how an application is being ran. All that is requested from the user is a functioning software which is then given to the cloud service provider. The cloud service provider is responsible fro deciding how and where the computation happens in the cloud. Moreover, this enables the developers to use only one programming language and design the software for a single platform since it is ran only in the cloud. By edge computing the situation differs significantly. Most of the platforms utilized by edge computing are heterogeneous. The runtime and resources of different platforms may differ. Therefore developers face a serious problem in order to design a service which can function properly on all types of platforms. [14] [10]
A possible solution to this challenge could be the concept of computing stream. It is defined as a flow or series of functions/computations which can happen anywhere on the data path. Those functions/computations could range from a single aspect of a service/application to a whole functionality of a service/application. The user can decide where the processing of data should happen and what data

should be transported. Therefore, most of data can be processed on the edge devices (what the main idea of edge computing is) and less functions/computations can be trusted to the different heterogeneous systems along the path. What is more transport costs are additionally reduced.[10]

6.2 Naming

When it comes to programming a system which communicates with a great number of other systems and devices the naming scheme is of great importance. It is crucial for data communication to identify things and address them. By edge computing there is currently no naming scheme which has been standardized. Because of the large number of IoT devices and other edge nodes we can assume that each of them has its own structure and way of providing a service. Therefore developers need to examine and understand numerous protocols for communication in order to be able to design a reliable service. A naming scheme capable of fulfilling the demands of edge computing should pay a lot of attention to privacy and security as well as be able to cope with dynamic networks and mobility of things. Nowadays we have standardized naming schemes such as DNS or URI which are able to satisfy the needs of cloud computing but prove to be not enough in order to be implemented in edge computing. Furthermore the most famous and typical naming scheme based on IP addresses seems to be too heavy and complex considering the fact that most of the edge nodes are resource constrained.[10] [14]
Two naming schemes have been proposed for the concept of edge computing but they still have some drawbacks which stop them from being generally accepted. Named Data Networking is the first one which has a hierarchical name structure. It proves to be human friendly but lacks the ability to separate data information from hardware information which is a serious security drawback. Moreover it requires additional proxy in order to be used with more communication protocols such as ZigBee or Bluetooth. MobilityFirst is the second proposed scheme which tackles the problem of NDN by being able to separate hardware information. On the other hand MobilityFirst requires a global unique identification which is far from being human friendly.[10] [14]
In [10] there is a proposed concept of a naming scheme for a smaller and more local network of edge devices. The idea is to let the edgeOS to name the different devices in a human friendly way. A structure for the name of the device is: (location).(role).(description of the data which is provided). For example in a smart home where an edgeOS is responsible for managing the devices could send information about the current temperature of the the air conditioner in the living room in the following way: livingroom.airconditioner.currenttemperature. And it could be interpreted by an application as: "The current temperature of the air conditioner in the living room is ..." .This seems to be a simple naming scheme which helps application to obtain and interpret data about numerous devices in a fast way. Furthermore, it provides better service management and programmability for the service providers.

6.3 Service Management

In order for the edge computing to be a reliable system some fundamental features need to be covered. Firstly there needs to be a good differentiation of information. It means that service need to be clearly prioritized. For example data which is classified as emergency data needs to processed before any other data. Secondly extensibility is really important. It allows the user to add a new device easy to the system without worrying about compatibility. Isolation of applications and service is the third crucial point. A failure of a service or an application should not obstruct the functioning of the whole system. And last but not least, we need to pay attention to reliability. When a failure occurs it could be caused by many reasons. It is a good idea for the service to be able to detect the right reason for the failure and inform the user. To achieve this however all of the nodes involved in the network should be able to send reliably status or diagnosis information. Furthermore compared to WiFi and Bluetooth the connection reliability of edge nodes is not pleasing. Therefore data sensing and communication cannot be classified as reliable.[10]

6.4 Security and Privacy

It is well known that data is at its most vulnerable state when it is being transmitted. By cloud computing data needs to travel long distances before being stored or processed and hence the time period in which it can be hijacked is great. By edge computing data needs to be transmitted at significantly shorter distances or not at all. Thus attackers have little or no opportunity in hijacking sensitive data.[8] However a significant issues concerning security and privacy still remain. First of all a great number of devices generate sensitive user data. It is really important for this data to be really well secured. For example, by extracting data about the commodity usages of a house an attacker could determine when the owner is present and when not. The edge nodes are owned by third party providers and some of them are not as secured as others. Therefore data could be exposed to serious attacks when stored there. It is a problem to provide all of the edge nodes with the same security. Today there are currently developed technologies which defend data on edge nodes but they are resource hungry. Some of the edge nodes do not have the needed resources in order to use those methods of protection.
Ownership of data has always been a discussed question especially nowadays with all of the privacy problems which the end users are facing. When storing data on servers provided by a third party there are a lot of privacy issues concerning who has more control over the data. Therefore, it is a good idea to store the data as close to the edge as possible even on the edge of the network itself and providing the end user with full rights and control over their own data.[10] [14]

18

7 Conclusion

With the growing numbers of devices which people are using and the integration of new services which require a heavy amount of data, we are in a great need of accelerating the data processing methods. The concept of edge computing seems to be the right extension of the current cloud computing model.The internet is slowly moving from a centralized control to the edge of the network. In the paper we presented edge computing - the idea of processing data at the edge of the network - as a technology which could significantly assist the bright future of the internet. We discussed how it differs from the traditional cloud model by utilizing the data generators and other nodes the data path in order to perform faster computing. A great plus of the concept is that it would not require a new complex hardware but the opposite, it uses the present devices. And ,what is more, its functionality is based on innovative and well developed technologies in the networking sector such as SDN and NFV. Then we introduced possible ways, how we can integrate it in the present mobile network. Edge computing is establishing itself as an important aspect of achieving 5G. The advantages which come with the integration of edge computing are numerous. We discussed its ability to accelerate the response time of the offered services as well as decrease the traffic through the network. It is a step closer to more environmental friendly IT with its ability to reduce power consumption. Moreover, it provides new storage opportunities and helps to tackle some of the issues concerning the privacy of cloud computing. Furthermore, we took a look at the possible application of edge computing. We saw that it could play a great role in different aspects of our lives. Its usefulness scales on different levels - from helping in our everyday life by enabling smart homes to accelerating the whole internet by assisting the content providers. Edge computing could become a significant part of our environment. Last but not least we paid attention to the challenges which it is facing. Since edge computing is still a developing technology it is normal for it to have its still unsolved problems. On the other hand we introduced possible solutions which are currently being researched and could be brought to life in the near future. To sum up edge computing is still a concept which needs to be deeply examined and tested but it seems to be a technology which is coming in the near future and it will be here to stay.

References

[1] Nasir Abbas et al. “Mobile edge computing: A survey”. In: *IEEE Internet of Things Journal* 5.1 (2017), pp. 450–465.
[2] Luigi Atzori, Antonio Iera, and Giacomo Morabito. “The internet of things: A survey”. In: *Computer networks* 54.15 (2010), pp. 2787–2805.
[3] “Cisco Global Cloud Index 2016-2021 White Paper”. In: ().
[4] “Cloud Computing”. In: *Wikipedia* ().
[5] Robert L Grossman. “The case for cloud computing”. In: *IT professional* 11.2 (2009), pp. 23–27.

[6] Yun Chao Hu et al. “Mobile edge computing—A key technology towards 5G”. In: *ETSI white paper* 11.11 (2015), pp. 1–16.

[7] Pavel Mach and Zdenek Becvar. “Mobile edge computing: A survey on architecture and computation offloading”. In: *IEEE Communications Surveys & Tutorials* 19.3 (2017), pp. 1628–1656.

[8] Saksham Mittal, Neelam Negi, and Rahul Chauhan. “Integration of edge computing with cloud computing”. In: *2017 International Conference on Emerging Trends in Computing and Communication Technologies (ICETCCT)*. IEEE. 2017, pp. 1–6.

[9] Jakob Nielsen. “Response Times: The 3 Important Limits”. In: ().

[10] Weisong Shi et al. “Edge computing: Vision and challenges”. In: *IEEE Internet of Things Journal* 3.5 (2016), pp. 637–646.

[11] J Srinivas, K Venkata Subba Reddy, and A MOIZ Qyser. “Cloud computing basics”. In: *International journal of advanced research in computer and communication engineering* 1.5 (2012), pp. 343–347.

[12] Xiang Sun and Nirwan Ansari. “EdgeIoT: Mobile edge computing for the Internet of Things”. In: *IEEE Communications Magazine* 54.12 (2016), pp. 22–29.

[13] Tarik Taleb et al. “On multi-access edge computing: A survey of the emerging 5G network edge cloud architecture and orchestration”. In: *IEEE Communications Surveys & Tutorials* 19.3 (2017), pp. 1657–1681.

[14] Wei Yu et al. “A survey on the edge computing for the Internet of Things”. In: *IEEE access* 6 (2017), pp. 6900–6919.

[15] Zitterbart. “Telematik Vorlesung”. In: ().

Vergleich von Feuchtesensoren in Bezug auf Genauigkeit Proseminar Mobile Computing 03.05.2019

Ilia Chupakhin
Betreuer Jan Formanek

[1] Karlsruher Institut für Technologie, Kaiserstraße 12, 76131 Karlsruhe, Deutschland
info@kit.edu
https://www.kit.edu/
[2] Technology for Pervasive Computing (TECO), Vincenz-Prießnitz-Straße 1,76131 Karlsruhe, Deutschland
sekretariat@teco.edu
https://www.teco.edu/

Zusammenfassung. Bestimmte Modelle von Feuchtesensoren wurden mit einem Referenzsensor in Bezug auf Genauigkeit verglichen. Der Referenzsensor ist SHT75. Die zu vergleichenden Sensoren sind SHT31, HTU21D, BME280, DHT22. Es waren jeweils vier Exemplare von SHT31, HTU21D, DHT22 und drei Exemplare von BME280 vorhanden. Der Referenzsensor war ein Einzelstück. Die Messungen wurden bei vier unterschiedlichen relativen Luftfeuchtigkeitsniveaus durchgeführt. Die gemessenen Werte wurden mithilfe von statistischen Methoden analysiert und anschließend wurde anhand der untersuchten Stichprobe auf die zu erwartende Genauigkeit der gesamten Population von gegebenen Sensoren geschlossen.

Schlüsselwörter: Sensor · Luftfeuchtigkeit · Vergleich · SHT75 · SHT31 · HTU21D · BME280 · DHT22

1 Einleitung

1.1 Motivation

Es gibt eine große Auswahl von Feuchtesensoren auf dem Markt. Die wichtigsten Kriterien bei der Wahl eines Sensors sind der Preis und die Messgenauigkeit. Die beiden Kriterien korrelieren miteinander: üblicherweise, je höher der Preis ist, umso höher ist die Messgenauigkeit. Doch manchmal kostet ein Sensor fünf- oder zehnmal so viel wie ein anderer, obwohl laut ihren Datenblättern der teurere nur um ein Prozent präziser die Luftfeuchtigkeit messen kann als der billigere. Der Preisunterschied wird umso spürbarer, wenn man die Sensoren in großen Mengen braucht. Deshalb will man sich für billigere Sensoren entscheiden, wenn ein solcher Präzisionsunterschied für den beabsichtigten Einsatzzweck nur wenig oder

komplett irrelevant ist. Allerdings entspricht die in den Datenblättern angegebene Messgenauigkeit manchmal nicht der tatsächlichen. Darüber hinaus fehlen oft die Angaben über die zu erwartende Streuung von Messwerten. Diese Probleme sind insbesondere bei billigen Sensoren öfter anzutreffen. Deswegen wollte man zuerst eine kleine Menge von Sensoren kaufen und ihre Messgenauigkeit experimentell überprüfen, bevor man die Sensoren in großen Mengen einkauft.

1.2 Zielsetzung

Im Rahmen des Proseminars wird eine Stichprobe von vier unterschiedlichen Modellen der Feuchtesensoren mit einem Referenzsensor in Bezug auf Messgenauigkeit verglichen. Von jedem Modell außer dem Referenzsensor werden mehrere Exemplare untersucht. Die Messungen werden bei vier unterschiedlichen relativen Luftfeuchtigkeitsstufen durchgeführt. Danach werden die gesammelten Daten einer statistischen Analyse unterzogen. Basierend auf der statistischen Analyse wird eins der untersuchten Modelle von Feuchtesensoren gefunden, dessen Messwerte den Messwerten vom Referenzsensor am nächsten liegen.

1.3 Begriffe und Abkürzungen

Luftfeuchtigkeitsstufe oder Luftfeuchtigkeitsniveau - relative Luftfeuchtigkeit 50%, 60%, 70% oder 80%.
RH(kommt von **r**elative **h**umidity) - relative Luftfeuchtigkeit.
Mit Luftfeuchtigkeit wird die relative Luftfeuchtigkeit gemeint.
Mit Sensor wird Feuchtesensor gemeint.
Mit Testsensor wird einer der mit dem Referenzsensor zu vergleichenden Sensoren gemeint, also HTU21D, SHT31, BME280 oder DHT22.

2 Vorbereitung auf das Messexperiment

Bevor das Messexperiment durchgeführt werden konnte, mussten die dafür benötigten Soft- und Hardwarekomponenten erstellt beziehungsweise zusammengesetzt werden. Außerdem musste eine passende experimentelle Umgebung eingerichtet werden.

2.1 Hardware

Die Datenblätter für die benutzten Hardware-Elemente sind im Literaturverzeichnis verlinkt.
Referenzsensor: SHT75
Die zu vergleichenden Sensoren: SHT31, HTU21D, BME280, DHT22
Mikrocontroller: NodeMCU ESP32
SD-Speicherkartenmodul: Pollin
SD-Speicherkarte: Kingston 16GB

Lochrasterplatine, Kabel, Buchsenleisten
Micro-USB Kabel und Laptop

Die Buchsenleisten wurden auf die Lochrasterplatine gelötet und verkabelt. Alle Sensoren, der Mikrocontroller und das SD-Speicherkartenmodul wurden in die Buchsenleisten eingesteckt. Die SD-Speicherkarte wurde in das SD-Speicherkartenmodul eingelegt. Der Mikrocontroller wurde über ein Micro-USB-Kabel zum Laptop angeschlossen. Siehe die Abbildung 1.

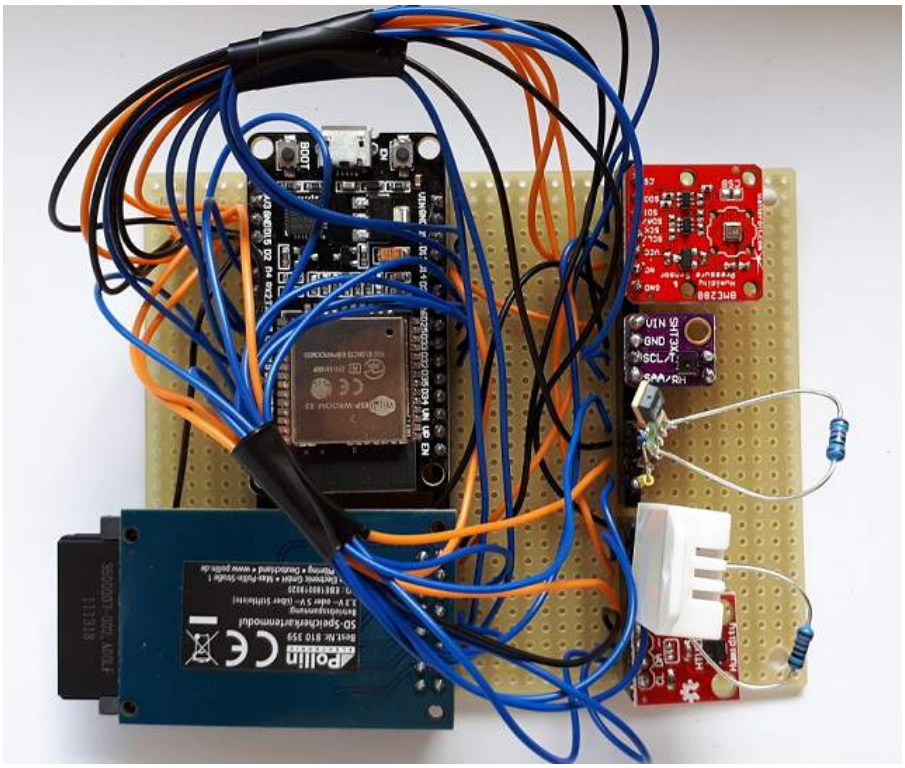


Abb. 1. Platine mit Sensoren

2.2 Software

Zum Steuern der Hardware-Elementen wurde ein Programm in der Entwicklungsumgebung Arduino (Version 1.8.9) geschrieben. Das Programm ist im Anhang zu finden. Zum Datenaustausch wurde der I^2C-Datenbus benutzt. Für alle Sensoren sowie für den Mikrocontroller mussten noch zusätzlich externe Bibliotheken installiert werden. Bei manchen der installierten Bibliotheken war es nicht

vorgesehen, dass man die PIN-Nummern für serial clock und serial data Kanäle nach seiner Wahl eingeben kann. Diese Funktionalität war aber notwendig, weil mehrere Sensoren zu einem Mikrocontroller angeschlossen werden mussten. Deswegen wurden folgende Funktionen zusätzlich zu den bereits vorhandenen implementiert:

- In der Datei Adafruit_SHT31.h:

```
boolean begin(int sda, int scl, uint8_t i2caddr = SHT31_DEFAULT_ADDR);
```

- In der Datei Adafruit_SHT31.cpp:

```
boolean Adafruit_SHT31::begin(int sda, int scl, uint8_t i2caddr) {
  Wire.begin(sda, scl);
  _i2caddr = i2caddr;
  reset();
  return true;
}
```

- In der Datei Adafruit_HTU21DF.h:

```
boolean begin(int sda, int scl);
```

- In der Datei Adafruit_HTU21DF.cpp:

```
boolean Adafruit_HTU21DF::begin(int sda, int scl) {
  Wire.begin(sda,scl);
  reset();
  Wire.beginTransmission(HTU21DF_I2CADDR);
  Wire.write(HTU21DF_READREG);
  Wire.endTransmission();
  Wire.requestFrom(HTU21DF_I2CADDR, 1);
  return (Wire.read() == 0x2); // after reset should be 0x2
}
```

Das geschriebene Programm funktioniert folgendermaßen:
Nach dem Einschalten des Mikrocontrollers wird eine neue Textdatei auf der SD-Speicherkarte einmal erstellt. Die Temperatur- und Luftfeuchtigkeitswerte werden von allen Sensoren einmal pro Sekunde ausgelesen. Die Werte werden temporär auf dem Mikrocontroller gespeichert. Nach zehn Auslesezyklen werden die gespeicherten Werte in die erstellte Textdatei hingeschrieben. Danach wird das Programm wie vorher abgearbeitet.

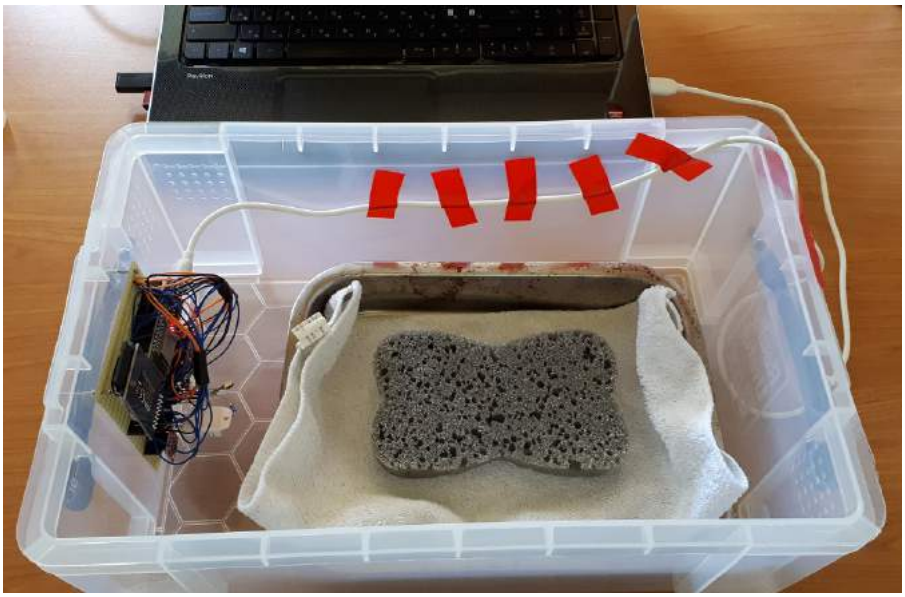


Abb. 2. Messaufbau

2.3 Messaufbau und Umgebung für das Messexperiment

Das Messexperiment wurde in einem Zimmer mit der Luftfeuchtigkeit 48-52% bei der Temperatur 27-31°C durchgeführt. Die Platine mit Sensoren wurde in einer Plastikkiste an die Wand befestigt. In der Kiste wurde eine Metallschüssel mit einem feuchten Tuch und Schwamm platziert. Siehe die Abbildung 2.

3 Durchführung des Messexperimentes

3.1 Planung des Messexperimentes

Die Messung wird bei jeweils 50, 60, 70 und 80% RH durchgeführt. Die Messwerte werden einmal pro Sekunde ausgelesen. Für jede der vier Luftfeuchtigkeitsstufen werden 170 Messzyklen durchgeführt. Die Messung startet bei 50% RH. Während des Messexperimentes wird die relative Luftfeuchtigkeit stufenweise bis 80% erhöht und anschließend wieder bis 50% gesenkt. Das Messexperiment wird für jedes Exemplar von Testsensoren durchgeführt.

3.2 Vernachlässigungen und Anmerkungen

– Aufgrund von Einschränkungen der experimentellen Umgebung und des Messaufbaues darf die Luftfeuchtigkeit in der experimentellen Umgebung im Bereich ±2% von der gewünschten schwanken und wird somit als konstant betrachtet.

- Um die Luftfeuchtigkeit in der Plastikkiste während der Messung konstant zu halten, wird der Kistendeckel manipuliert.

- Die Sensoren besitzen unterschiedliche Antwortzeiten. Laut den Datenblättern sind die Antwortzeiten: 8 Sekunden für SHT75, 10 Sekunden für HTU21D, 8 Sekunden für SHT31, 1 Sekunde für BME280, nicht angegeben für DHT22. Damit die Antwortzeiten möglichst kleine Auswirkung auf die Messergebnisse haben, wird nach dem Wechseln zu der nächsten Luftfeuchtigkeitsstufe zwei Minuten gewartet, bis die nächste Messung startet.

- Die einzelnen Sensoren werden nicht parallel, sondern nacheinander vom Mikrocontroller angesprochen. Trotzdem wird angenommen, dass die Luftfeuchtigkeitswerte von allen fünf Sensoren zum gleichen Zeitpunkt ausgelesen werden, weil das Auslesen aller Sensoren insgesamt weniger als 200 Millisekunden dauert und in der experimentellen Umgebung sind jegliche Änderungen der Luftfeuchtigkeit innerhalb so einer kurzen Zeitspanne vernachlässigbar.

- Aus Kostengründen war die Stichprobe relativ klein. Es waren ein Exemplar von dem Referenzsensor, drei Exemplare von BME280 und jeweils vier Exemplare von den anderen Sensoren vorhanden. Die Größe der Stichprobe spiegelt sich in der Breite des Konfidenzintervalles wider.[1]

- Die Messung bei der steigenden und anschließend bei der senkenden Luftfeuchtigkeit war notwendig, um die Hysterese von Sensoren herauszufinden. Das heißt, die Messewerte bei derselben Luftfeuchtigkeit können unterschiedlich ausfallen abhängig davon, ob die Luftfeuchtigkeit vor der Messung gestiegen oder gesunken ist.

3.3 Ablauf des Messexperimentes

Die relative Luftfeuchtigkeit im Zimmer wurde im Bereich 48-52% während des gesamten Messexperimentes konstant gehalten. Die Plastikkiste wurde auf den Tisch nahe des Laptops gestellt. Die ersten Exemplare von den Testsensoren wurden angeschlossen. Der Mikrocontroller wurde zum Laptop angeschlossen. Die Messwerte waren auf dem Bildschirm zu sehen und wurden einmal pro Sekunde aktualisiert. Die Messung bei der Luftfeuchtigkeit 50% wurde durchgeführt. Danach wurde die Metallschüssel mit einem feuchten Tuch und Schwamm in die Plastikkiste eingelegt. Die Luftfeuchtigkeit in der Kiste ist auf 60% gestiegen. Die Messung bei der Luftfeuchtigkeit 60% wurde durchgeführt. Danach wurde der Deckel auf die Kiste gelegt, so dass sie etwa zu 2/3 abgedeckt war. Die relative Luftfeuchtigkeit in der Kiste ist auf 70% gestiegen. Die Messung bei der Luftfeuchtigkeit 70% wurde durchgeführt. Danach wurde die Kiste mit dem Deckel komplett abgedeckt. Die Luftfeuchtigkeit in der Kiste ist auf 80% gestiegen. Die

[1] Siehe das Kapitel Auswertung der Messergebnisse

Messung bei der Luftfeuchtigkeit 80% wurde durchgeführt. Anschließend wurden analog die Messungen bei der absteigenden Luftfeuchtigkeit durchgeführt. Das Messexperiment wurde für alle Exemplare von Testsensoren durchgeführt (insgesamt vier Mal).

4 Auswertung der Messergebnisse

Nachdem das Messexperiment abgeschlossen war, mussten die Messergebnisse mithilfe von statistischen Methoden ausgewertet werden. Die Textdateien mit den Messdaten wurden im Programm Apache OpenOffice Calc bearbeitet.
Zuerst wurden die Messdaten manuell gefiltert. Die Messungen während den Übergängen zwischen Luftfeuchtigkeitsstufen wurden entfernt. Auch die Messungen in den nächsten zwei Minuten nach dem Übergang mussten entfernt werden, um den Einfluss von unterschiedlichen Antwortzeiten der Sensoren auf die statistische Auswertung zu reduzieren. Während der Messung kam es manchmal zu den leichten Überschreitungen von den vereinbarten Grenzen von ±2% RH. Diese Daten wurden ebenso aus den zu analysierenden Messdaten entfernt.
Danach wurde in jeder Messung und für jeden Sensor die Abweichung von den Referenzwerten ausgerechnet.

$$A = \varphi_{\text{ref}} - \varphi \tag{1}$$

A - Abweichung, φ_{ref} - relative Luftfeuchtigkeit gemessen von dem Referenzsensor, φ - relative Luftfeuchtigkeit gemessen von einem Testsensor.
Die Abbildungen drei bis sechs sind Streudiagramme, die die Abweichungen der Messwerte von den Referenzwerten während der Messung bei 50% RH zeigen. Die Streudiagramme für die Messungen bei den anderen Luftfeuchtigkeitsstufen sind im Anhang zu finden. Zur Erinnerung, die Messwerte wurden einmal pro Sekunde ausgelesen und für jede Luftfeuchtigkeitsstufe wurden 170 Messwerte analysiert. An der Stelle sollte es angemerkt werden, dass die Kurven auf den Streudiagrammen für die Messungen bei 50 und 80% RH glatter als für die Messungen bei 60 und 70% RH sind. Das liegt daran, dass während der Messungen bei 60 und 70% RH die Luftfeuchtigkeit stärker schwankte als bei 50 und 80% RH. Der Kistendeckel musste oft hin- und hergeschoben werden, damit die Luftfeuchtigkeit im Bereich 60±2%RH beziehungsweise 70±2%RH bleibt. Da die Sensoren unterschiedliche Antwortzeiten haben, schwankten auch die Abweichungen zwischen den einzelnen Messungen stärker als während der Messungen bei 50% und 80% RH.

Anschließend wurde für jedes Exemplar der Testsensoren und für jede Luftfeuchtigkeitsstufe die absolute durchschnittliche Abweichung von den Referenzwerten ausgerechnet.

$$\overline{A} = \frac{1}{170} \cdot \sum_{i=1}^{170} |A_i| \tag{2}$$

Absolute durchschnittliche Abweichung bedeutet, dass es irrelevant ist, ob zum

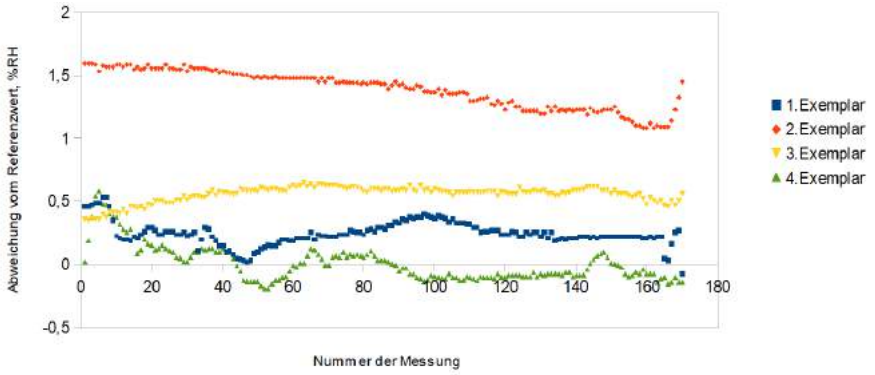


Abb. 3. HTU21DF Abweichung von Referenzwerten während der Messung bei 50% RH

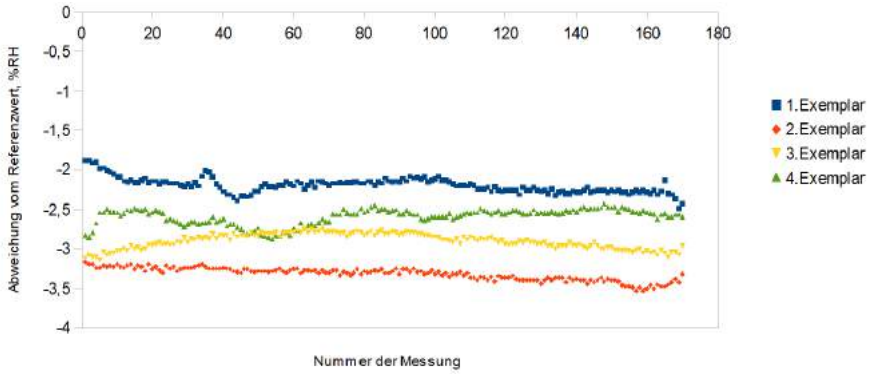


Abb. 4. SHT31 Abweichung von Referenzwerten während der Messung bei 50% RH

Beispiel der gemessene Wert um 3% RH größer oder kleiner als der Referenzwert ist. Wichtig ist nur, dass er um drei Prozent von dem Referenzwert abweicht. Die Motivation hinter der Entscheidung, einen absoluten Wert auszurechnen statt auf das Vorzeichen zu achten, wird am Besten durch ein kleines Gegenbeispiel ersichtlich sein: bei der ersten Messung betrage die Abweichung +5% RH und bei der zweiten -6% RH. Die durchschnittliche Abweichung wäre also $(5+(-6))/2 = 0.5$. Dann würde man sich denken, dass der Sensor nur eine kleine Abweichung von den Referenzwerten hat, obwohl es nicht stimmt.
Nachdem die Messwerte für die einzelnen Exemplare von Sensoren analysiert wurden, konnte man mit der Analyse der gesamten Stichprobe anfangen und anschließend Aussagen über die gesamte Population von Sensoren treffen. Allerdings war die Stichprobe relativ klein (drei bis vier Exemplare von Testsensoren). Auch die Angaben über die Varianz der gesamten Population haben gefehlt. Eine

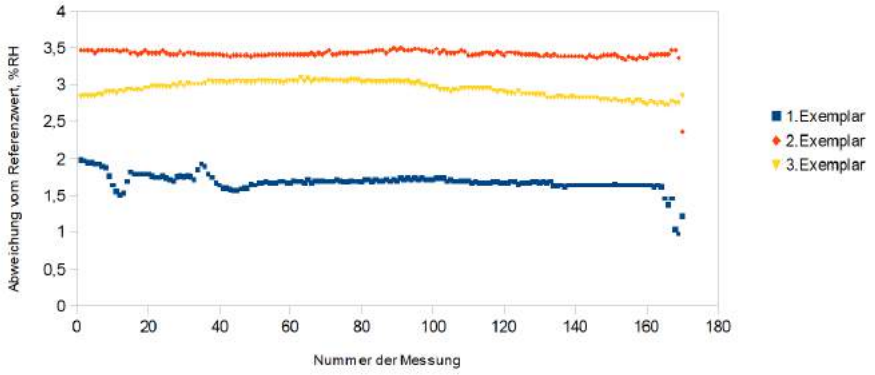


Abb. 5. BME280 Abweichung von Referenzwerten während der Messung bei 50% RH

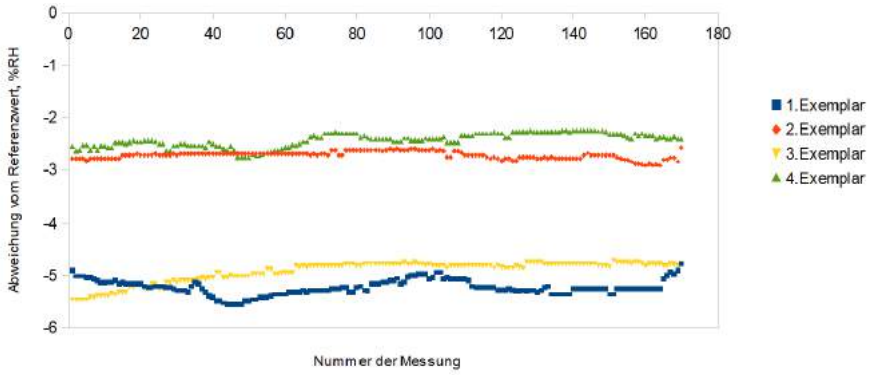


Abb. 6. DHT22 Abweichung von Referenzwerten während der Messung bei 50% RH

Lösung des Problems besteht darin, dass man die unbekannte Populationsvarianz durch die Stichprobenvarianz ersetzt und zum Ausrechnen der Konfidenzintervalle die Koeffizienten für die t-Verteilung (auch als Studentsche Verteilung bekannt) nimmt, die auch von der Größe der Stichprobe abhängig sind.
Zuerst wurden für jedes Modell der Sensoren der Mittelwert und die Varianz von der absoluten mittleren Abweichung ausgerechnet und zwar für jede Luftfeuchtigkeitsstufe separat. Die Hysterese ist in die Rechnung mit einbezogen, denn es wurden die absoluten mittleren Abweichungen beim Anstieg und beim Abstieg RH für jede Luftfeuchtigkeitsstufe genommen.

$$\mu = \frac{1}{m} \cdot \sum_{i=1}^{m} \overline{A}_i \tag{3}$$

$$\sigma^2 = \frac{1}{m-1} \cdot \sum_{i=1}^{m} (\mu - \overline{A}_i)^2 \tag{4}$$

$$m = \begin{cases} 2 \cdot j & \text{falls die Luftfeuchtigkeitsstufe} \neq 80\% \\ j & \text{sonst} \end{cases}$$

j - Stichprobengröße, μ - Mittelwert, σ^2 - Varianz
Dann wurde der Standardfehler des Mittelwertes ausgerechnet.

$$SEM = \frac{\sigma}{\sqrt{j}} \tag{5}$$

Mit den ausgerechneten Werten konnte man schließlich die Konfidenzintervalle bestimmen. Da die Stichprobe relativ klein war, hat man sich für die 90%-Konfidenzintervalle statt der typischen 95%-Konfidenzintervalle entschieden.

$$K = [\kappa_{\min}; \kappa_{\max}] = [\mu - t \cdot SEM; \mu + t \cdot SEM] \tag{6}$$

t ist der t-Koeffizient aus der Tabelle für die gegebene Stichprobengröße.
Auch die durchschnittliche Hysterese wurde ausgerechnet.

$$\overline{H} = \frac{1}{j} \cdot \sum_{i=1}^{j} |\overline{A}_{\text{Anstieg}} - \overline{A}_{\text{Abstieg}}| \tag{7}$$

j - Stichprobengröße, $\overline{A}_{\text{Anstieg}}$ und $\overline{A}_{\text{Abstieg}}$ - durchschnittliche absolute Abweichung bei steigender beziehungsweise sinkender Luftfeuchtigkeit.
In den Tabellen 1 - 5 sind die ausgerechneten Werte zu sehen.

Tabelle 1. HTU21D Stichprobenanalyse, % RH

Luftf.	Mittelwert	Varianz	Std.fehler des Mit.wert.	Hysterese	Konf.intervall Min	Konf.intervall Max
50%	0,4742	0,1617	0,2011	0,3448	0,0010	0,9473
60%	1,2861	0,4154	0,3223	0,9903	0,5278	2,0444
70%	0,8166	0,2559	0,2529	0,2634	0,2214	1,4117
80%	0,9750	0,5393	0,3672		0,1111	1,8390

Tabelle 2. SHT31 Stichprobenanalyse, % RH

Luftf.	Mittelwert	Varianz	Std.fehler des Mit.wert.	Hysterese	Konf.intervall Min	Konf.intervall Max
50%	3,0389	0,3625	0,3010	0,5717	2,3306	3,7472
60%	2,9858	0,1892	0,2175	0,5825	2,4741	3,4976
70%	1,2604	0,3337	0,2888	0,5490	0,5807	1,9400
80%	0,5345	0,1404	0,1874		0,0937	0,9754

Tabelle 3. BME280 Stichprobenanalyse, % RH

Luftf.	Mittelwert	Varianz	Std.fehler des Mit.wert.	Hysterese	Konf.intervall Min	Konf.intervall Max
50%	2,4127	0,5690	0,4355	0,5347	1,1409	3,6844
60%	2,1172	1,4835	0,7032	0,9336	0,0638	4,1706
70%	1,5420	1,9040	0,7967	0,7583	-0,7843	3,8683
80%	3,4388	0,6496	0,4653		2,0800	4,7975

Tabelle 4. DHT22 Stichprobenanalyse, % RH

Luftf.	Mittelwert	Varianz	Std.fehler des Mit.wert.	Hysterese	Konf.intervall Min	Konf.intervall Max
50%	4,2123	1,7667	0,6646	0,7747	2,6486	5,7761
60%	4,4267	4,8240	1,0982	0,7657	1,8427	7,0107
70%	5,3804	6,1087	1,2358	1,2253	2,4726	8,2883
80%	6,0669	8,6937	1,4743		2,5980	9,5358

Während der Analyse der gemessenen Werten von den DHT22 Sensoren hat man gemerkt, dass die Messwerte von dem ersten Exemplar deutlich stärker von den Referenzwerten abweichen als die von den anderen Exemplaren. Eine mögliche Erklärung dafür ist, dass das erste Exemplar defekt ist. Deshalb wurden auch noch die Messwerte von DHT22 Sensoren ohne die Messwerte von dem ersten Exemplar analysiert. Die Tabelle 5 zeigt die Ergebnisse.

Tabelle 5. Stichprobenanalyse DHT22 ohne das erste Exemplar, % RH

Luftf.	Mittelwert	Varianz	Std.fehler des Mit.wert.	Hysterese	Konf.intervall Min	Konf.intervall Max
50%	3,7681	1,4861	0,7038	0,8221	1,7129	5,8233
60%	3,4143	1,7723	0,7686	0,7600	1,1699	5,6586
70%	4,2464	2,3401	0,8832	1,4252	1,6675	6,8254
80%	4,7185	2,1318	0,8430		2,2570	7,1800

In dem Kapitel Schlussfolgerungen werden die Werte für DHT22 Sensoren aus der Tabelle 5 benutzt.

5 Schlussfolgerungen

Die Tabellen 6, 7 zeigen die absoluten Abweichungen der Sensoren von den Referenzwerten und die Konfidenzintervalle.

Bei den Luftfeuchtigkeitsstufen 50%, 60% und 70% haben die HTU21D Sensoren die kleinste Abweichung von den Referenzwerten. Bei den 50% und 70% ist die Abweichung kleiner als 1 % RH und bei 60% kleiner als 1,5% RH. Bei 80% RH haben die SHT31 Sensoren die kleinste Abweichung von den Referenzwerten, obwohl die HTU21D Sensoren immer noch um weniger als 1% RH von den Referenzwerten abweichen.

Bei den Luftfeuchtigkeitsstufen 50%, 60% und 70% haben die HTU21D Sensoren die kleinsten Konfidenzintervalle. Bei 80% RH haben die SHT31 Sensoren

Tabelle 6. absolute Abweichungen der Sensoren von den Referenzwerten in % RH

Luftfeuchtigkeit	HTU21D	SHT31	BME280	DHT22
50%	0,4742	3,0389	2,4127	3,7681
60%	1,2861	2,9858	2,1172	3,4143
70%	0,8166	1,2604	1,5420	4,2464
80%	0,9750	0,5345	3,4388	4,7185

Tabelle 7. Konfidenzintervalle

Luftfeuchtigkeit	HTU21D	SHT31	BME280	DHT22
50%	[0,0010; 0,9473]	[2,3306; 3,7472]	[1,1409; 3,6843]	[1,7129; 5,8233]
60%	[0,5278; 2,0444]	[2,4741; 3,4977]	[0,0638; 4,1706]	[1,1699; 5,6586]
70%	[0,2214; 1,4117]	[0,5807; 1,9400]	[-0,7843; 3,8683]	[1,6675; 6,8254]
80%	[0,1111; 1,8390]	[0,0937; 0,9754]	[2,0800; 4,7975]	[2,2570; 7,1800]

das kleinste Konfidenzintervall.

Die HTU21D, SHT31 und BME280 Sensoren haben die Hysterese kleiner als 1% RH, was in den meisten Fällen als typisch und akzeptabel gilt. Die DHT22 Sensoren haben bei 50% und 60% RH die Hysterese kleiner als 1% RH, bei 70% RH aber fast 1.5% RH.

Aus der durchgeführten Untersuchung kann man Folgendes schlussfolgern:

- Wenn man die Luftfeuchtigkeit im Bereich 50 bis 70% messen will, sind die HTU21D Sensoren die beste Wahl. Falls man die Luftfeuchtigkeit nahe 80% messen muss, empfehlen sich die SHT31 Sensoren, obwohl die HTU21D Sensoren immer noch eine gute Wahl wäre.

- Wenn man keine HTU21D Sensoren kaufen kann, wären dann die SHT31 Sensoren eine Alternative. Man muss aber damit rechnen, dass sich die gemessenen Werte bei den Luftfeuchtigkeiten 50-60% RH von 2 bis 4% RH von den Referenzwerten abweichen.

- Die BME280 und DHT22 Sensoren sind nicht zu empfehlen wegen der zu großen und zu stark schwankenden Messwerte. Darüber hinaus haben die DHT22 Sensoren eine lange Antwortzeit(bei hohen Luftfeuchtigkeiten bis zu 2 Minuten).

Literatur

1. Henze, N., Kadelka, D.: Wahrscheinlichkeitstheorie und Statistik für Studierende der Informatik und des Ingenieurwesens. Karlsruhe (2010)
2. Population und Stichprobe, `http://www.mesosworld.ch/lerninhalte/Grund_PopStich/de/text/Grund_PopStich.pdf`

3. Von der Stichprobe zur Grundgesamtheit, http://www.janteichmann.me/downloads/study_material/statistik/2015/01/21/stichprobeGrundgesamtheit/
4. Wikipedia, https://www.wikipedia.de/
5. Datenblatt Sensor SHT75, http://www.mouser.com/ds/2/682/Sensirion_Humidity_SHT7x_Datasheet_V5-469726.pdf
6. Datenblatt Sensor HTU21D, https://www.amsys.de/downloads/data/HTU21D-HTU21DF-AMSYS-datasheet.pdf
7. Datenblatt SHT31, https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/0_Datasheets/Humidity/Sensirion_Humidity_Sensors_SHT3x_Datasheet_digital.pdf
8. Datenblatt Sensor BME280, https://ae-bst.resource.bosch.com/media/_tech/media/datasheets/BST-BME280-DS002.pdf
9. Datenblatt Sensor DHT22, https://cdn-shop.adafruit.com/datasheets/Digital+humidity+and+temperature+sensor+AM2302.pdf
10. Datenblatt Mikrocontroller NodeMCU-ESP32, http://anleitung.joy-it.net/wp-content/uploads/2018/07/SBC-NodeMCU-ESP32-Datenblatt_V1.3.pdf
11. Datenblatt SD-Speicherkartenmodul Pollin, https://www.pollin.de/productdownloads/D810359B.PDF
12. Datenblatt SD-Speicherkarte Kingston, https://www.kingston.com/datasheets/sdc4_en.pdf

A Anhang

A.1 Streudiagramme

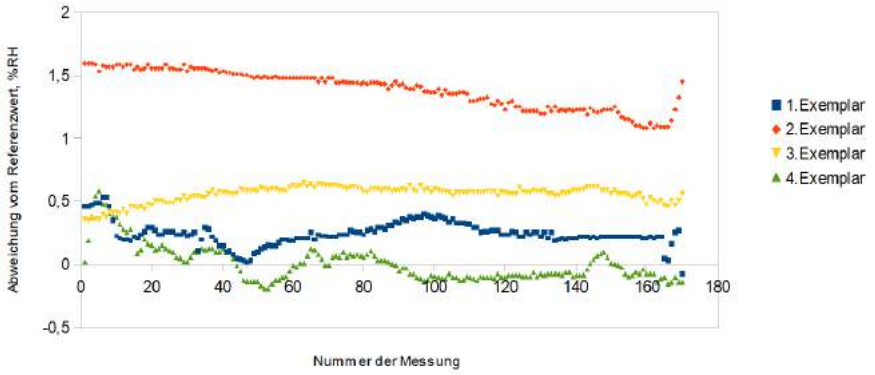


Abb. 7. HTU21DF Abweichung von Referenzwerten während der Messung bei 50% RH

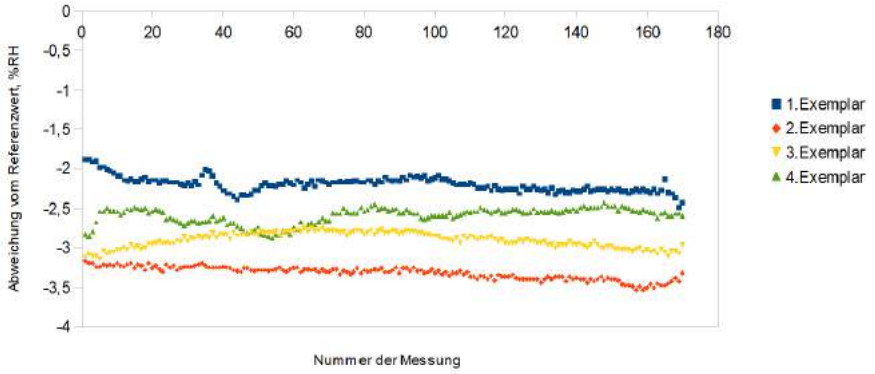


Abb. 8. SHT31 Abweichung von Referenzwerten während der Messung bei 50% RH

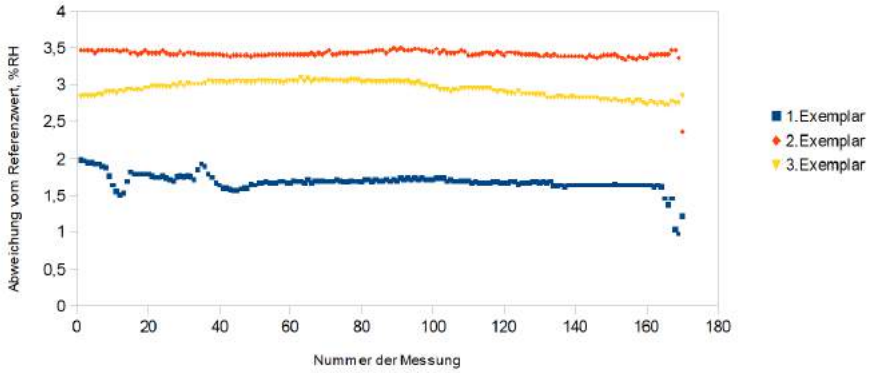


Abb. 9. BME280 Abweichung von Referenzwerten während der Messung bei 50% RH

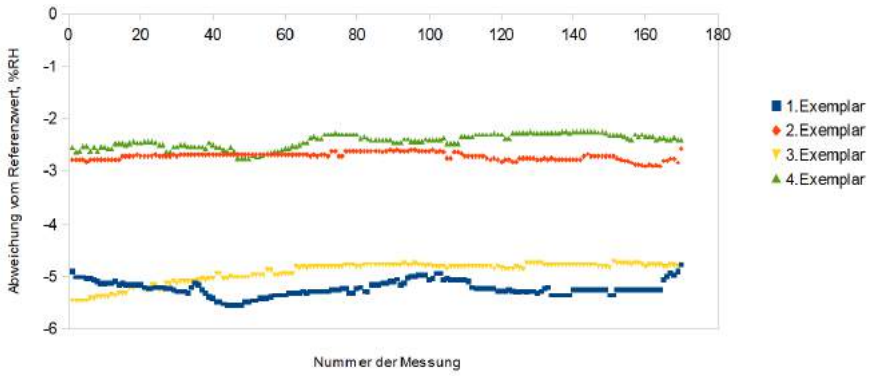


Abb. 10. DHT22 Abweichung von Referenzwerten während der Messung bei 50% RH

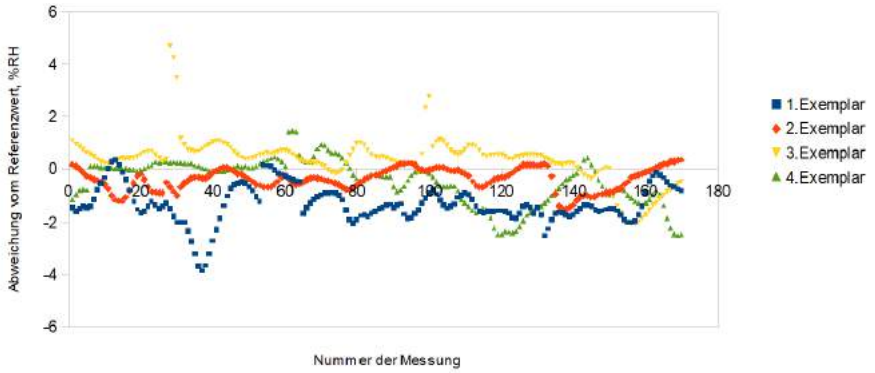


Abb. 11. HTU21DF Abweichung von Referenzwerten während der Messung bei 60% RH

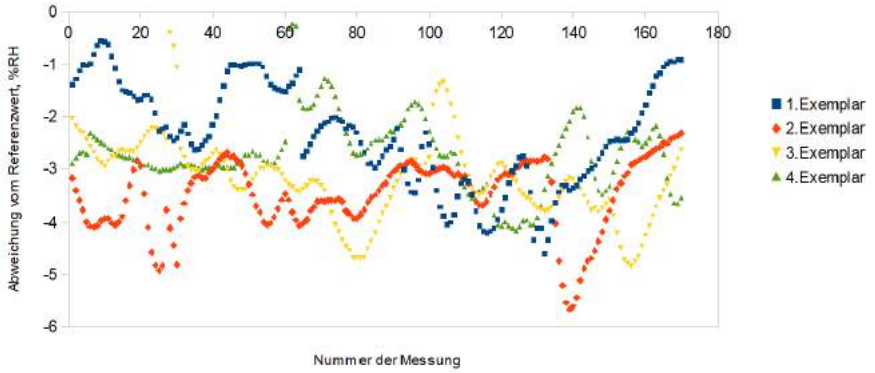


Abb. 12. SHT31 Abweichung von Referenzwerten während der Messung bei 60% RH

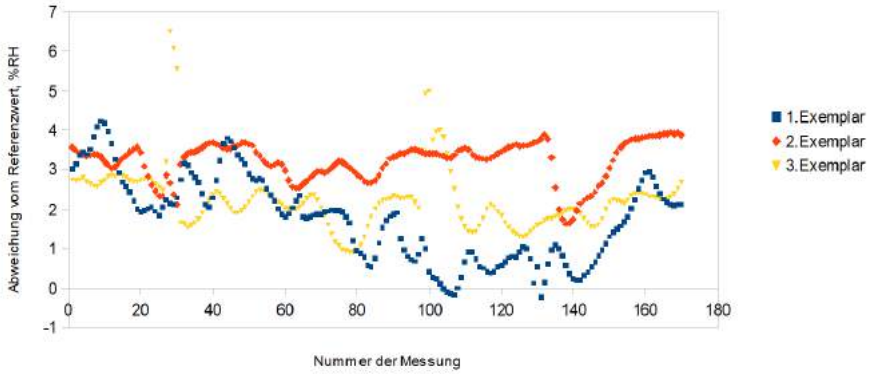


Abb. 13. BME280 Abweichung von Referenzwerten während der Messung bei 60% RH

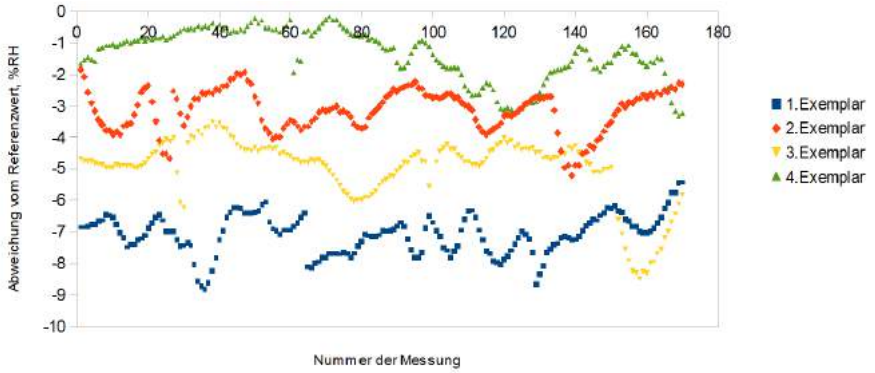


Abb. 14. DHT22 Abweichung von Referenzwerten während der Messung bei 60% RH

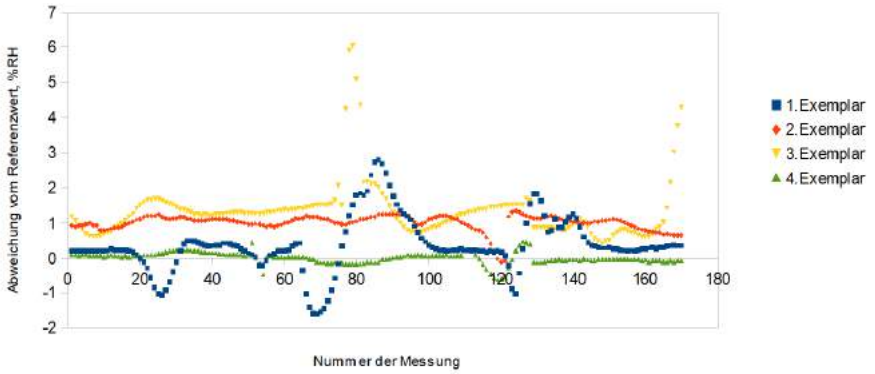


Abb. 15. HTU21DF Abweichung von Referenzwerten während der Messung bei 70% RH

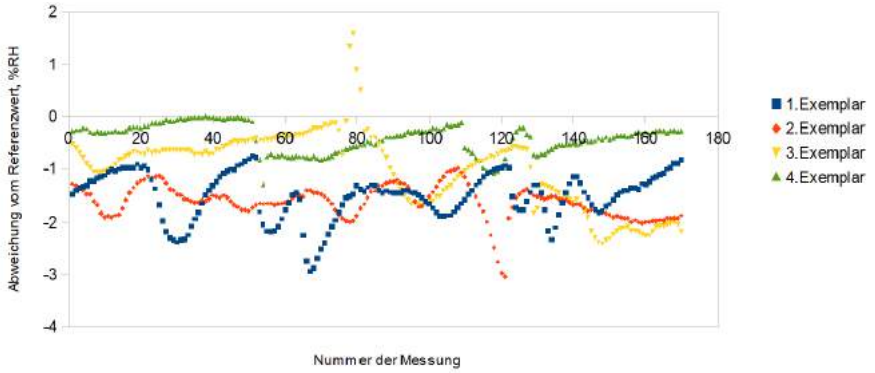


Abb. 16. SHT31 Abweichung von Referenzwerten während der Messung bei 70% RH

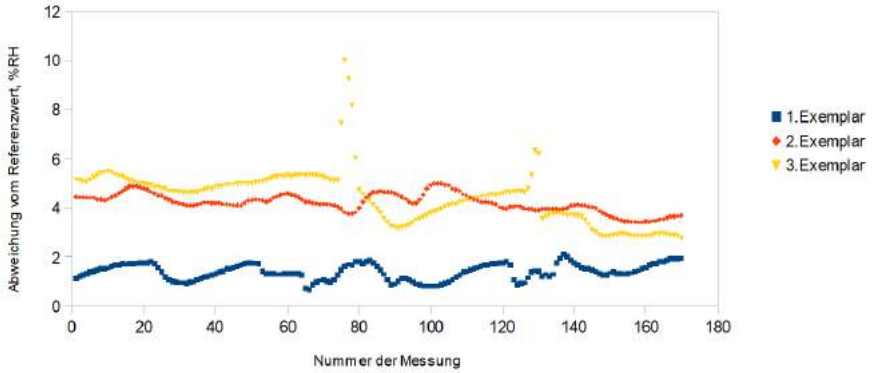


Abb. 17. BME280 Abweichung von Referenzwerten während der Messung bei 70% RH

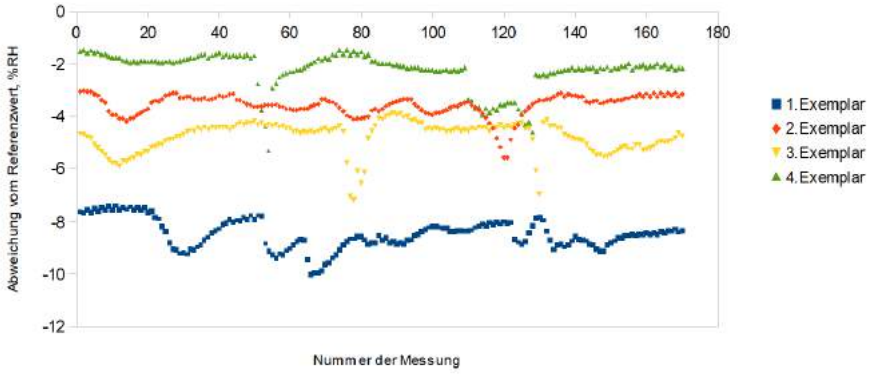


Abb. 18. DHT22 Abweichung von Referenzwerten während der Messung bei 70% RH

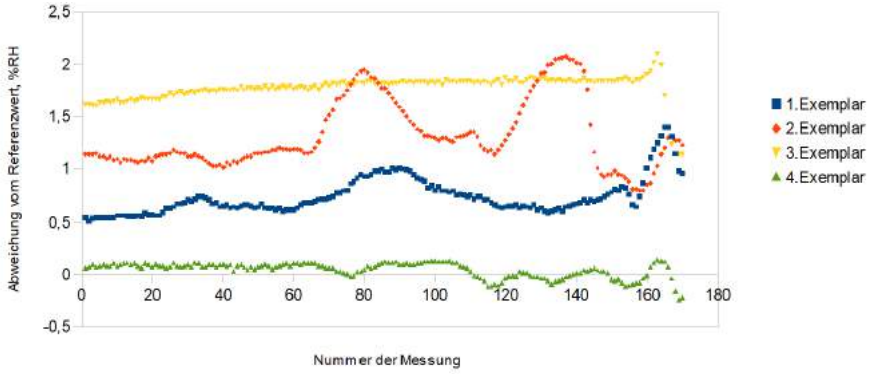


Abb. 19. HTU21DF Abweichung von Referenzwerten während der Messung bei 80% RH

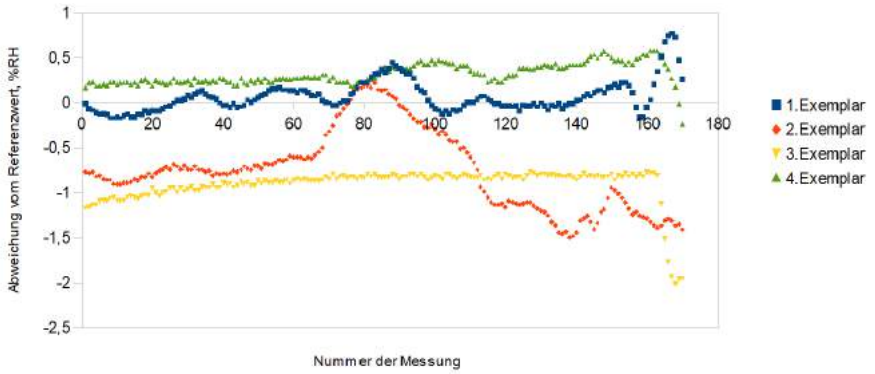


Abb. 20. SHT31 Abweichung von Referenzwerten während der Messung bei 80% RH

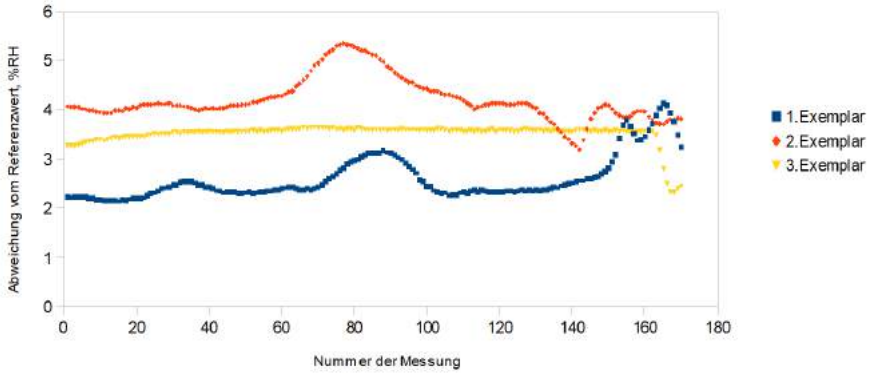


Abb. 21. BME280 Abweichung von Referenzwerten während der Messung bei 80% RH

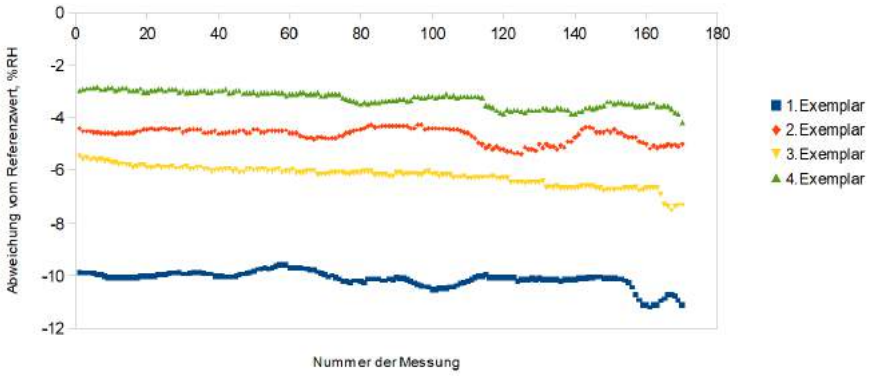


Abb. 22. DHT22 Abweichung von Referenzwerten während der Messung bei 80% RH

A.2 Programm

```
#include "SD.h"
#include <Wire.h>
#include "Adafruit_HTU21DF.h"
#include "Adafruit_SHT31.h"
#include <Adafruit_BME280.h>
#include <Sensirion.h>
#include "DHT.h"
#include "FS.h"
#include "SPI.h"
#include "TimeLib.h"

#define SDA_SHT75 32
#define SCL_SHT75 33

#define SDA_HTU21 25
#define SCL_HTU21 26

#define SDA_SHT31 13
#define SCL_SHT31 14

#define SDA_BME280 21
#define SCL_BME280 22

#define SDA_DHT22 4
#define DHTTYPE DHT22

#define NUM_MEASUREMENTS 10

/*Temperatur, Feuchtigkeit, Zeit wann
gemessen wurde * fuenf Sensoren 3*5 = 15*/
#define NUM_PARAMETERS 15

#define DELAY_TIME 500
#define STRING_LENGTH 300


Sensirion sht75 = Sensirion(SDA_SHT75, SCL_SHT75);
float temperature_sht75;
float humidity_sht75;
float dewpoint_sht75;

Adafruit_HTU21DF htu21 = Adafruit_HTU21DF();

Adafruit_SHT31 sht31 = Adafruit_SHT31();
```

```
Adafruit_BME280 bme280 = Adafruit_BME280();
TwoWire wire_bme280 = TwoWire(5);

DHT dht22(SDA_DHT22, DHTTYPE);

/*measurements[x][y]:
  x ist i-te Messung
  y=0 Temp.   SHT75
  y=1 Feucht. SHT75
  y=2 die seit dem Einschalten des Mikrokontrollers vergangene Zeit
      in Millisekunden SHT75
  y=3 Temp.   HTU21
  y=4 Feucht. HTU21
  y=5 die seit dem Einschalten des Mikrokontrollers vergangene Zeit
      in Millisekunden HTU21
  y=6 Temp.   SHT31
  y=7 Feucht. SHT31
  y=8 die seit dem Einschalten des Mikrokontrollers vergangene Zeit
      in Millisekunden SHT31
  y=9 Temp.   BME280
  y=10 Feucht.BME280
  y=11 die seit dem Einschalten des Mikrokontrollers vergangene Zeit
      in Millisekunden BME280
  y=12 Temp.  DHT22
  y=13 Feucht.DHT22
  y=14 die seit dem Einschalten des Mikrokontrollers vergangene Zeit
      in Millisekunden DHT22
*/
float measurements[NUM_MEASUREMENTS][NUM_PARAMETERS];

int counter = 0;
int totalMeasurementCounter = 0;
char fileName[32];


void doMeasurement() {

  sht75.measure(&measurements[counter][0], &measurements[counter][1],
                &dewpoint_sht75);
  measurements[counter][2] = (float)millis();

  htu21.begin(SDA_HTU21, SCL_HTU21);
  measurements[counter][3] = htu21.readTemperature();
  measurements[counter][4] = htu21.readHumidity();
```

```
  measurements[counter][5] =  (float)millis();

  sht31.begin(SDA_SHT31, SCL_SHT31);
  measurements[counter][6] = sht31.readTemperature();
  measurements[counter][7] = sht31.readHumidity();
  measurements[counter][8] =  (float)millis();

  measurements[counter][9] = bme280.readTemperature();
  measurements[counter][10] = bme280.readHumidity();
  measurements[counter][11] = (float)millis();

  measurements[counter][12] = dht22.readTemperature();
  measurements[counter][13] = dht22.readHumidity();
  measurements[counter][14] =  (float)millis();

}

void printLastMeasurement() {

  Serial.print("SHT75 Temp: "); Serial.print(measurements[counter][0]);
  Serial.print("; Hum: "); Serial.print(measurements[counter][1]);
  Serial.print("; Time: "); Serial.println(measurements[counter][2]);

  Serial.print("HTU21DF Temp: "); Serial.print(measurements[counter][3]);
  Serial.print("; Hum: "); Serial.print(measurements[counter][4]);
  Serial.print("; Time: "); Serial.println(measurements[counter][5]);

  Serial.print("SHT31 Temp: "); Serial.print(measurements[counter][6]);
  Serial.print("; Hum: "); Serial.print(measurements[counter][7]);
  Serial.print("; Time: "); Serial.println(measurements[counter][8]);

  Serial.print("BME280 Temp: "); Serial.print(measurements[counter][9]);
  Serial.print("; Hum: "); Serial.print(measurements[counter][10]);
  Serial.print("; Time: "); Serial.println(measurements[counter][11]);

  Serial.print("DHT22 Temp: "); Serial.print(measurements[counter][12]);
  Serial.print("; Hum: "); Serial.print(measurements[counter][13]);
  Serial.print("; Time: "); Serial.println(measurements[counter][14]);
  Serial.println("");

}

void writeMeasurementsOnSdCard() {
  char buffer[NUM_MEASUREMENTS][STRING_LENGTH];
  for(int i = 0; i < NUM_MEASUREMENTS; i++) {
```

```
    String measurement = String(totalMeasurementCounter) + ";"
                       + String(measurements[i][0]) + ";"
                       + String(measurements[i][1]) + ";"
                       + String(measurements[i][2])
                       + ";" + String(measurements[i][3])
                       + ";" + String(measurements[i][4])
                       + ";" + String(measurements[i][5])
                       + ";" + String(measurements[i][6])
                       + ";" + String(measurements[i][7])
                       + ";" + String(measurements[i][8])
                       + ";" + String(measurements[i][9]) + ";"
                       + String(measurements[i][10]) + ";"
                       + String(measurements[i][11])
                       + ";" + String(measurements[i][12])
                       + ";" + String(measurements[i][13]) + ";"
                       + String(measurements[i][14]);


    measurement.toCharArray(buffer[i],STRING_LENGTH);
    totalMeasurementCounter++;
  }
  appendFile(SD, fileName, buffer);
}


void createFileName(fs::FS &fs) {
  String fileNameStr = "/measurements_";
  char fileNameChar[32];
  int numOfFiles = 0;
  File dir = fs.open("/");
  while(dir.openNextFile()) {
    numOfFiles++;
  }
  fileNameStr = fileNameStr + String(numOfFiles) + ".txt";
  fileNameStr.toCharArray(fileName,32);
  Serial.print("Created name: ");
  Serial.println(fileName);
}

void writeFile(fs::FS &fs, const char * message){
    createFileName(fs);
    Serial.printf("Writing file: %s\n", fileName);
    File file = fs.open(fileName, FILE_WRITE);
    if(!file){
        Serial.println("Failed to open file for writing");
```

```
        return;
    }
    if(file.print(message)){
        Serial.println("File written");
    } else {
        Serial.println("Write failed");
    }
    file.close();
}

void appendFile(fs::FS &fs, const char * path,
                char messages[NUM_MEASUREMENTS][STRING_LENGTH]){
    Serial.printf("Appending to file: %s\n", path);

    File file = fs.open(path, FILE_APPEND);
    if(!file){
        Serial.println("Failed to open file for appending");
        return;
    }
    for(int i = 0; i < NUM_MEASUREMENTS; i++) {
      if(file.println(messages[i])){
          Serial.println("Message appended");
      } else {
          Serial.println("Append failed");
      }
    }

    file.close();
}


void setup() {
  Serial.begin(9600);
  Serial.println("Beginning");

  dht22.begin();

  wire_bme280.begin(SDA_BME280,SCL_BME280);
  bme280.begin(&wire_bme280);

  if(!SD.begin()){
      Serial.println("Card Mount Failed");
      return;
  }
  uint8_t cardType = SD.cardType();
```

```
  if(cardType == CARD_NONE){
      Serial.println("No SD card attached");
      return;
  }

  Serial.print("SD Card Type: ");
  if(cardType == CARD_MMC){
      Serial.println("MMC");
  } else if(cardType == CARD_SD){
      Serial.println("SDSC");
  } else if(cardType == CARD_SDHC){
      Serial.println("SDHC");
  } else {
      Serial.println("UNKNOWN");
  }

  uint64_t cardSize = SD.cardSize() / (1024 * 1024);
  Serial.printf("SD Card Size: %lluMB\n", cardSize);

  Serial.printf("Total space: %lluMB\n", SD.totalBytes() / (1024 * 1024));
  Serial.printf("Used space: %lluMB\n", SD.usedBytes() / (1024 * 1024));
  writeFile(SD,
   "Meas_numb;SHT75_temp;SHT75_hum;SHT75_time;
   HTU21DF_temp;HTU21DF_hum;HTU21DF_time;
   SHT31_temp;SHT31_hum;SHT31_time;
   BME280_temp;BME280_hum;BME280_time;DHT22_temp;
   DHT22_hum;DHT22_time\n");

}


void loop() {
  if(counter == NUM_MEASUREMENTS) {
    writeMeasurementsOnSdCard();
    counter = 0;
  }
  doMeasurement();
  printLastMeasurement();
  counter++;
  delay(DELAY_TIME);
}
```

Review von Strukturlernalgorithmen

Marco Goltze

Karlsruher Institut für Technologie, Kaiserstraße 12, Karlsruhe, Germany
marco.goltze@kit.edu

Abstract. Diese Arbeit gibt zum Einstieg in das Thema eine Einführung in Wahrscheinlichkeitstheorie und probabilistische graphische Modelle und stellt daraufhin die verschiedenen Möglichkeiten zum Lernen in probabilistischen graphischen Modellen dar. Dabei gibt es in der Literatur eine Vielzahl von Ansätzen, die dazu geeignet sind, die Parameter oder die Struktur von probabilistischen graphischen Modellen abzuändern, zu verbessern oder sie Struktur sogar gänzlich neu zu erlernen. Diese Arbeit betrachtet das Lernen von Parametern nicht im Detail und nur der Vollständigkeit halber. Stattdessen wird sich vor allem auf Verfahren zum Lernen der Strukturen in probabilistischen graphischen Modellen konzentriert, wobei zwischen gerichteten und ungerichteten Graphen sowie zwischen constraintbasierten, scorebasierten und hybriden Ansätzen unterschieden wird. Nachdem die verschiedenen Algorithmen vorgestellt worden sind, werden sie in Hinblick auf verschiedene Aspekte miteinander verglichen. Es zeigt sich dabei, dass große Unterschiede in der Komplexität der Ansätze bestehen und sich die Performance ebenfalls stark unterscheidet. Zudem wird herausgestellt werden, dass es sehr stark von den Daten und Variablen abhängig ist, wie gut ein Ansatz für einen konkreten Anwendungsfall geeignet ist.

Keywords: Bayes'sche Netze, Markov Netze, Probabilistische graphische Modelle, Strukturlernen.

1 Einleitung

Ein probabilistisches graphisches Modell ist ein Netzwerk, das aus Knoten besteht, die durch Kanten miteinander verbunden sind. Der Begriff probabilistisch kommt hier zur Anwendung, weil mit jeder Kante eine Wahrscheinlichkeitsverteilung einhergeht, die das Verhältnis zwischen den Knoten, die für Zufallsvariablen stehen, beschreibt [1]. Die Kanten, die die Zufallsvariablen verbinden, können in einem solchen Modell entweder gerichtet oder ungerichtet sein. Sind die Kanten gerichtet, spricht man von einem Bayes'schen Netz. Sind die Kanten dagegen nicht gerichtet, so nennt man dieses probabilistische graphische Modell ein Markov-Netz [2].

Man bezeichnet den Graphen auch als „Struktur" und die bedingten Wahrscheinlichkeiten als „Parameter". Liegen verschiedene Zufallsvariablen vor, so kann entweder durch Expertenwissen oder über mathematische Verfahren zum Strukturlernen die Struktur ermittelt werden [3]. Innerhalb der Strukturlernverfahren ist zunächst zwischen scorebasierten und constraintbasierten Ansätzen zu unterscheiden. Während in

scorebasierten Ansätzen die relative Häufigkeitsverteilung nicht bekannt ist und anhand der Daten die Struktur des Netzwerks durch Vergleich verschiedener Muster ausgewählt wird, suchen constraintbasierte Ansätze nach einem Netzwerk, das sowohl die Markov Bedingung, als auch die „bedingten Unabhängigkeiten in der Wahrscheinlichkeitsverteilung“ [3] erfüllt [3]. Fortgeschrittene Algorithmen nutzen nicht nur constraint- oder scorebasierte Elemente, sondern enthalten Bestandteile beider Kategorien, sodass man hier von hybriden Ansätzen sprechen kann [4]. Sobald die Struktur eines Netzwerkes durch die verschiedenen Methoden ermittelt worden ist, können Verfahren aus dem Bereich des Parameterlernens Anwendung finden, die dazu in der Lage sind, in einem vorliegenden Graphen eine Wahrscheinlichkeitsverteilung ermitteln [3].

In dieser Arbeit sollen vor allem zwei Fragen beantwortet werden. Die erste lautet, welche Verfahren zum Lernen der Struktur von probabilistischen graphischen Modellen in der Literatur vorgestellt worden sind. Darauf aufbauend lautet die zweite Frage, wie sich diese Verfahren voneinander unterscheiden. Dies bezieht sich sowohl auf den Aufbau der Algorithmen als auch auf die Anwendungsmöglichkeiten und die Qualität der Ergebnisse, die die verschiedenen Ansätze liefern.

Inhaltlich wird diese Arbeit zunächst in einige theoretische Grundlagen einführen, damit die späteren Kapitel darauf aufbauen können. Kapitel 2 behandelt daher einige elementare Begriffe der Wahrscheinlichkeitstheorie und führt in probabilistische graphische Modelle ein. Dabei wird zwischen Bayes’schen Netzen und Markov-Netzen unterschieden. Im Anschluss daran wird in Kapitel 3 aufgezeigt, wie die verschiedenen Arten des Lernens klassifiziert werden können und es wird ein Überblick über die konkreten Ansätze gegeben. Der Fokus wird dabei auf Strukturlernverfahren liegen, während Verfahren des Parameterlernens nur der Vollständigkeit halber erwähnt werden. Kapitel 4 vergleicht die zuvor vorgestellten Strukturlernalgorithmen in Hinblick auf verschiedene Kriterien miteinander, bevor abschließend die Ergebnisse zusammengefasst werden und ein Ausblick gegeben wird.

2 Grundlagen

In diesem Kapitel soll zur Einführung in das Thema zunächst ein Überblick über die theoretischen Grundlagen gegeben werden. Dazu wird zunächst über die Grundlagen der Wahrscheinlichkeitstheorie zum Satz von Bayes hingeführt. Zudem wird eine Einführung in probabilistische graphische Modelle gegeben, sodass im Anschluss daran die vorgestellten Themen bei Bayes’schen Netzen und Markov-Netzen zusammengebracht werden können. Zudem wird auch auf mögliche Anwendungsfelder der beiden Arten graphischer Modelle eingegangen, um die theoretischen Aspekte etwas leichter greifbar zu machen.

2.1 Absolute Wahrscheinlichkeit

Die Wahrscheinlichkeit für das Eintreten eines Ereignisses A kann durch

$$P(A) \tag{1}$$

ausgedrückt werden. Dies wird als absolute Wahrscheinlichkeit bezeichnet und kann nur dann verwendet werden, wenn „das Zufallsexperiment noch nicht begonnen hat oder über das laufende bzw. beendete Zufallsexperiment keinerlei Information vorliegt“ [5].

2.2 Wahrscheinlichkeitsverteilung

Eine Wahrscheinlichkeitsverteilung ordnet in einem Zufallsexperiment jedem möglichen Resultat des Experimentes dessen Eintrittswahrscheinlichkeit zu. Je nachdem, ob die betrachteten Merkmale qualitativ oder quantitativ sind, spricht man von stetigen, bzw. von diskreten Wahrscheinlichkeitsverteilungen [6].

Formal bedeutet dies, dass ein Experiment mit den möglichen Resultaten Ω, sowie einer Menge S gegeben ist, die die zu messenden Ausgänge α enthält. Die Eintrittswahrscheinlichkeiten in Ω summieren sich zu 1 und jedes einzelne Event besitzt eine Wahrscheinlichkeit größer gleich 0. Zudem wird davon ausgegangen, dass die Wahrscheinlichkeit zweier diskreter Ereignisse α und β gemäß

$$P(\alpha \cup \beta) = P(\alpha) + P(\beta) \tag{2}$$

aufsummiert werden kann [2].

2.3 Bedingte Wahrscheinlichkeit

Sind im Vergleich zur absoluten Wahrscheinlichkeit bereits Informationen bekannt, so ändern sich durch das Nicht-Eintreten bestimmter Ereignisse unter Umständen die Wahrscheinlichkeiten für das Eintreffen des Ereignisses A und man nutzt statt der absoluten Wahrscheinlichkeit die sogenannte bedingte Wahrscheinlichkeit, die durch

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \tag{3}$$

beschrieben werden kann. Sie drückt die Wahrscheinlichkeit dafür aus, dass ein erstes Ereignis A eintritt, gegeben, dass ein zweites Ereignis B eingetreten ist bzw. eintritt. Das bedeutet, dass alle Kombinationsmöglichkeiten von A und B, in denen B nicht eintritt, nicht betrachtet werden müssen, wodurch ein Informationsgewinn entsteht. Es ist im Allgemeinen möglich, bei bedingten Wahrscheinlichkeiten die Produktregel wie folgt anzuwenden, sodass für gemeinsame Wahrscheinlichkeiten von A und B die Umformungen

$$P(A \cap B) = P(A|B) * P(B) = P(B|A) * P(A) \text{ für } P(A), P(B) > 0 \tag{4}$$

gültig sind [5].

2.4 Satz von Bayes

Man spricht vom „Satz der totalen (vollständigen) Wahrscheinlichkeit“ [5], wenn für ein Ereignis B die absolute Wahrscheinlichkeit P(B) nicht unter Zuhilfenahme der

absoluten Wahrscheinlichkeit P(A) eines Ereignisses A definiert wird. Anstelle von A können alle möglichen Zustände A_i mit den Eintrittswahrscheinlichkeiten $P(A_i)$ gewichtet und daraufhin aufsummiert werden. A wird nun also nicht länger als einzelnes Ereignis, sondern als die Menge von Ereignissen A_i betrachtet. Dabei geht man davon aus, dass diese Ereignisse disjunkt sind und es somit nicht möglich ist, dass mehrere Ereignisse A_i eintreten. Ebenso ist es unmöglich, dass keines der Ereignisse eintritt [5]. Mathematisch lässt sich dieser Sachverhalt durch

$$P(B) = \sum_{i=1}^{n} P(B|A_i) * P(A_i) \text{ mit } P(A_i) > 0 \; \forall \, i \tag{5}$$

ausdrücken.

Kombiniert man nun die bisher aufgezeigten Definition und Formeln miteinander, so lässt sich dadurch der Satz von Bayes beweisen [5]. Dabei handelt es sich um ein mathematisches Konstrukt zur Beschreibung bedingter Wahrscheinlichkeiten, das erstmal im Jahre 1763 von Thomas Bayes beschrieben worden ist [7]. Der Satz von Bayes und lässt sich mathematisch durch

$$P(A_k|B) = \frac{P(B|A_k)*P(A_k)}{P(B)} = \frac{P(B|A_k)*P(A_k)}{\sum_{i=1}^{n} P(B|A_i)*P(A_i)} \tag{6}$$

beschreiben [5] und wird vielfach in der vereinfachten Form

$$P(A|B) = \frac{P(B|A)*P(A)}{P(B)} \tag{7}$$

dargestellt. Hierbei wird der Kenntnisstand P(B) (a priori-Wahrscheinlichkeit) durch die bedingte Wahrscheinlichkeitsverteilung P(A|B) verbessert, sodass sich mit P(B|A) ein neuer Kenntnisstand (a posteriori-Wahrscheinlichkeit) ergibt [8]. Der Satz von Bayes ist damit die mathematische Formulierung eines Lernprozesses und stellt dar, „wie bei Erlangung neuer Informationen die Verteilung der beobachteten Variable (…) zu berechnen ist“ [8].

2.5 Probabilistische graphische Modelle

Ein probabilistisches graphisches Modell ist ein Netzwerk von Knoten, die durch Kanten miteinander verbunden sind. Ein solches Netzwerk hat die Eigenschaft, dass „jeder Knoten eine Zufallsvariable (oder eine Gruppe von Zufallsvariablen) repräsentiert und die Kanten die Wahrscheinlichkeitsverteilungen zwischen diesen Variablen ausdrücken“ [1]. Probabilistische graphische Modelle sind sehr gut zur Modellierung von Sachverhalten geeignet, da sie ein überaus intuitives Konzept sind. Dies liegt daran, dass die Modelle und deren Struktur einfach zu verstehen sind, was dazu führt, dass sich ebenso intuitiv ein solches Modell erstellen lässt. Ebenso lässt sich nur durch Analyse der Struktur feststellen, wie sich Abhängigkeiten und Unabhängigkeiten zwischen den Zufallsvariablen verhalten. Außerdem können „komplexe Berechnungen, die für Inferenz und Lernen in anspruchsvollen Modellen benötigt werden, in Form graphischer Manipulationen ausgedrückt werden, in denen die zugrundeliegenden mathematischen Ausdrücke implizit mitgeführt werden“ [1].

In einem probabilistischen graphischen Modell können die Kanten gerichtet oder ungerichtet sein. Sind die Kanten, die die Variablen verbinden, gerichtet, spricht man von einem Bayes'schen Netz. Hier drücken die Kanten einen Effekt der einen Variable auf die andere aus. Bayes'sche Netze zählen zu den wichtigsten Arten graphischer Modelle [1]. Sind die Kanten zwischen den Variablen dagegen nicht gerichtet, sondern ungerichtet, so nennt man dieses probabilistische graphische Modell ein Markov-Netz. In Markov-Netzen geben die Kanten nicht mehr den Effekt einer Zufallsvariablen auf eine andere an, sondern stehen vielmehr für eine Affinität zwischen diesen Variablen, die sich in beide Richtungen interpretieren lässt [2, 4].

2.6 Bayes'sche Netze

Von einem bayes'schen Netz spricht man also bei einem „annotierten, gerichteten, azyklischen Graphen, der eine gemeinsame Wahrscheinlichkeitsverteilung über einen Satz von Zufallsvariablen codiert" [9]. Der Begriff „annotiert" beschreibt hier, dass die Wahrscheinlichkeiten an den Kanten ausgewiesen werden, „gerichtet und azyklisch" sagt aus, dass jede Kante eine Richtung besitzen muss und es nicht möglich sein darf, ausgehend von einer Zufallsvariable wieder zu ebendieser zurückzukehren. Zudem bezeichnet man den Graph eines Bayes'schen Netzes auch als „Struktur" und die bedingten Wahrscheinlichkeiten als „Parameter" [3].

Im Folgenden wird ein einfaches Beispiel für ein bayes'sches Netz vorgestellt, in dem fünf Zufallsvariablen modelliert werden. Die Zufallsvariable A stehe dafür, dass eine Alarmanlage ausgelöst wird. Grund dafür kann entweder ein Einbruch B oder ein Erdbeben E sein. Die übrigen beiden Zufallsvariablen beschreiben den Sachverhalt, dass der Hausbesitzer telefonisch von seinen Nachbarn (N1, N2) über den Alarm informiert wird.

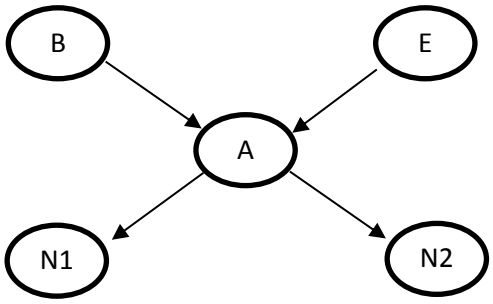


Fig. 1. Beispiel für ein bayes'sches Netz.
Quelle: Eigene Darstellung nach [10], Beispiel modifiziert.

Ein bayes'sches Netz drückt eine gemeinsame Verteilung P(X) der enthaltenen Zufallsvariablen aus, die durch

$$P(X) = \prod_{i=1}^{n} P(X|\, pa(X_i)) \tag{8}$$

beschrieben werden kann, wobei X die Zufallsvariablenmenge $\{X_1,\ldots,X_n\}$ und $pa(X_i)$ die Elternknoten des Knoten X_i darstellen [8]. Diese mathematische Definition drückt etwas aus, das man auch intuitiv vermuten würde, da sich die gemeinsame Verteilung aus dem Produkt der bedingten Wahrscheinlichkeiten über das gesamte Netz und der a priori-Wahrscheinlichkeit der Ausgangsknoten ergibt.

Bei der Analyse von Daten besitzen Bayes'sche Netze einige Vorteile gegenüber anderer Analysemethoden. Beispielsweise kann Expertenwissen eingebracht werden und es muss sich nicht nur auf die in den Daten enthaltenen Informationen beschränkt werden. Bayes'sche Netze können nicht nur mit vollständigen Datensätzen umgehen, sondern sind auch bei Datenbeständen mit fehlenden Werten hilfreich. Zudem kann das Overfitting des Modells verhindert werden und es lassen sich aus bayes'schen Netzen kausale Zusammenhänge ableiten [11].

Während man bei einer direkten Kante zwischen zwei Zufallsvariablen in einem Bayes'schen Netz immer von einer Korrelation ausgehen kann, sind diese nicht unbedingt voneinander unabhängig, wenn es keine direkte Kante zwischen ihnen gibt. Es gibt jedoch Fälle, in denen man Unabhängigkeit zwischen Zufallsvariablen unterstellen möchte. Dazu kann das Konzept der d-Separation genutzt werden, bei dem vier verschiedene Fälle zu unterscheiden sind, bei denen es keine direkte Kante zwischen zwei Variablen gibt [2].

- Der erste Fall ist eine indirekte kausale Verbindung. In diesem Fall liegt also ein Knoten Z zwischen den Knoten X und Y. Ist dies der Fall, so kann unterstellt werden, dass X keinen Einfluss auf Y hat, wenn Z bekannt ist. Ist Z dagegen nicht bekannt, so kann von einem Effekt ausgegangen werden [2]. In obigem Graphen ist eine solche Konstellation beispielsweise im Falle des Pfades B → A → N1 gegeben.
- Der zweite Fall ist ein indirekter Beweiseffekt, wobei X und Y im Vergleich zum ersten Fall vertauscht sind. Die Frage lautet hier, ob auch ein Zusammenhang unterstellt werden kann, wenn man den gerichteten Kanten entgegen ihrer Richtung folgt. Analog zum ersten Fall kann man einen Effekt nur annehmen, wenn Z nicht bekannt ist [2]. Im gezeigten Beispiel wäre dies derselbe Pfad wie im ersten Fall.
- Die dritte Möglichkeit der Verbindung ist, dass X und Y einen gemeinsamen Grund besitzen. Auch hier gilt, dass man Unabhängigkeit unterstellen kann, solange Z bekannt ist. Ist Z dagegen nicht beobachtet worden, kann keine Unabhängigkeit angenommen werden [2]. In oben gezeigtem Beispiel ist durch A ein gemeinsamer Grund für N1 und N2 gegeben.
- Ein wenig komplexer wird es im vierten und letzten Fall. Hier haben X und Y gemeinsam einen Effekt auf Z. Sobald Z oder eine der Zufallsvariablen, die von Z beeinflusst werden, beobachtet worden sind, kann man nicht von einer Unabhängigkeit zwischen X und Y ausgehen [2]. Im Beispiel stellt besitzen B und E die gemeinsame Folge A.

Bayes'sche Netze können in verschiedensten Anwendungsfällen eingesetzt werden. Ein einfaches Beispiel für die Anwendung bayes'scher Netze ist ein Naive-Bayes-Klassifikator. Dabei wird ein Objekt einer von mehreren Klassen zugeordnet, wobei sich die Wahrscheinlichkeit für ein Objekt x zu einer Klasse i zu gehören durch

7

$$P(i|x) = \frac{P(i) * P(x|i)}{\sum_{j=1}^{n} P(j) * P(x|j)} \quad (9)$$

beschreiben lässt. Dabei stellt x die Merkmale des Objektes in vektorieller Form dar. Abbildung 2 zeigt ein Beispiel für die Struktur eines Naive-Bayes-Klassifikator. Dabei gibt es sechs Variablen $\{X_1, \ldots, X_6\}$, die jeweils eine mögliche Fehlerart darstellen, die in einer Produktion auftreten kann. Wichtig ist hier, dass die verschiedenen Fehler voneinander unabhängig sind. Dies macht zum Beispiel Sinn, wenn man in einem Produktionsprozess bestimmen möchte, mit welcher Wahrscheinlichkeit ein produziertes Teil defekt ist und wie wahrscheinlich es ist, dass dieses Bauteil bestimmte Fehler aufweist. Reale Bayes'sche Netze sind in der Regel jedoch weitaus komplexer als es in den hier vorgestellten Beispielen der Fall gewesen ist [12].

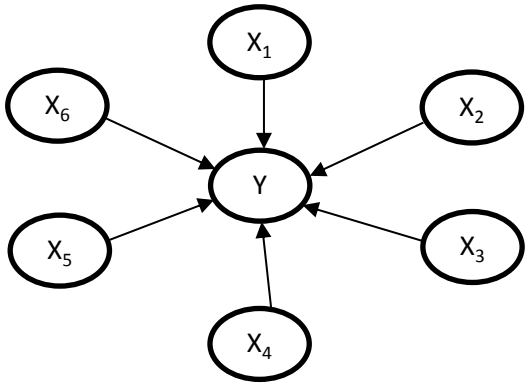


Fig. 2. Naive-Bayes-Klassifikator in einem Produktionsprozess.
Quelle: Eigene Darstellung nach [12].

2.7 Markov-Netze

Markov-Netze stellen eine weitere Untergruppe probabilistischer graphischer Modelle dar. Analog zu Bayes'schen Netzen steht auch hier ein Knoten stellvertretend für eine Variable. Der Unterschied besteht darin, dass in diesem Fall die Kanten nicht von einem Knoten zu einem anderen zeigen, sondern ungerichtet sind. Dadurch geben die Kanten nicht mehr den Effekt einer Variablen auf eine andere an, sondern stehen vielmehr für eine Affinität zwischen diesen Variablen, die sich in beide Richtungen interpretieren lässt. Komplexe Markov-Netze lassen sich vereinfachen, wenn für Zufallsvariablen Kontexte angenommen werden. In einem solchen Fall können diese fixierten Variablen aus dem Netz entfernt werden, was bei zentralen Variablen sogar dazu führen kann, dass nicht mehr nur ein Netzwerk, sondern mehrere, kleinere Netzwerke vorliegen, die im betrachteten Kontext voneinander unabhängig sind [2, 4].

Die nachfolgende Abbildung 3 zeigt ein einfaches Beispiel für ein Markov-Netz, das den Sachverhalt eines Studenten in einer Universität modelliert. Die Note N, die er in einem Kurs erhält, steht in Zusammenhang mit der Schwierigkeit des Kurses (S)

und seiner eigenen Intelligenz (I). Zudem wird hier modelliert, dass S und I nicht ebenfalls miteinander verbunden sind, weil auch die Kurswahl mit der Intelligenz zusammenhängt. Zudem gibt es Wechselwirkungen seiner Fröhlichkeit (F) mit Kursnote bzw. Job (J). Der Job steht außerdem im Zusammenhang mit I und N [2].

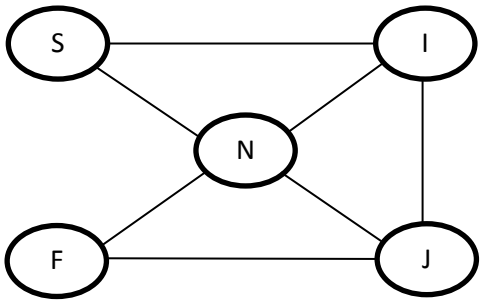


Fig. 3. Beispiel für ein Markov-Netz.
Quelle: Eigene Darstellung nach [2], Beispiel modifiziert.

Wie bei Bayes'schen Netzen kann man auch in Markov Netzen Aussagen über die Unabhängigkeit zwischen Knoten treffen. Zunächst lässt sich hier sagen, dass bei miteinander verbundenen Knoten selbstverständlich keine Unabhängigkeit unterstellt werden kann. Zweitens spielt es auch in diesem Fall für die Unabhängigkeit von Zufallsvariablen eine große Rolle, ob die Variablen, die auf einem Pfad zwischen zwei Knoten A und B liegen, beobachtet worden sind. Gibt es in einem Markov-Netz keinen Pfad, über den man von Knoten A zu Knoten B gelangt, ohne dass man mindestens eine beobachtete Variable passiert, so kann man Unabhängigkeit zwischen A und B unterstellen [4].

Ein typischer Fall, in dem Markov-Netze verwendet werden ist die maschinelle Bildverarbeitung. In diesem Zusammenhang spricht man nicht von Markov-Netzen, sondern von Markov Random Fields (MRFs). Hier wird jedem Pixel eine Zufallsvariable zugewiesen, die jeweils Kanten zu den direkten benachbarten Pixeln (bzw. Zufallsvariablen) aufweist. Das so entstehende Gitter kann durch die Messung der Gemeinsamkeiten verbundener Zufallsvariablen verwendet werden, um auf dem analysierten Bild Muster oder Objekte zu erkennen, das Bild zu segmentieren oder sogar die Bildqualität durch Identifikation von Rauschen zu verbessern [4].

3 Parameterlernen

Möchte man in einem vorliegenden Graphen eine Wahrscheinlichkeitsverteilung ermitteln, so finden Verfahren aus dem Bereich des Parameterlernens Anwendung [3]. Dabei wird unterscheiden, ob vollständige Daten zur Verfügung stehen oder nicht. Ist dies der Fall, so können beispielsweise über einen Maximum Likelihood-Schätzer

$$L = \frac{1}{N} \sum_i \sum_l \log P(x_i | pa(x_i), D_l) \quad (10)$$

für jeden Knoten direkt die Parameter bestimmt werden, wobei N die Anzahl der Datensätze und D die Daten selbst beschreibt. Dies kann dann über die Knoten aufsummiert werden, um die Log-Likelihood (Normalisiert) L zu erhalten [5].

Die Vorgehensweise zur Parameterschätzung ändert sich, wenn die Daten nicht vollständig bekannt sind. In diesem Fall ist es möglich, einen Expectation Maximation Algorithmus zu nutzen, welcher mehrere Schritte durchläuft, um die Parameter zu ermitteln. Dabei werden die fehlenden Daten geschätzt und dann iterativ angepasst, was nicht immer zu globalen, zumindest jedoch zu lokalen Maxima führt [5].

4 Strukturlernen in gerichteten Netzwerken

Die Anwendung von Strukturlernverfahren setzt ein vorhandenes Netzwerk voraus, das die zugrundeliegenden Sachverhalte möglichst gut abbildet. Beziehungen zwischen Zufallsvariablen und Wahrscheinlichkeitsverteilungen sind jedoch nicht per se von vornherein bekannt. Liegen verschiedene Zufallsvariablen vor, so kann entweder durch Expertenwissen oder über Strukturlernverfahren die Struktur ermittelt werden, sodass daraufhin ein gerichteter, azyklischer Graph vorliegt [3].

Die Algorithmen zum Lernen der Struktur Bayes'scher Netze können wiederum in zwei Kategorien unterteilt werden. Das Lernen kann entweder scorebasiert oder constraintbasiert erfolgen. Während in scorebasierten Ansätzen die relative Häufigkeitsverteilung nicht bekannt ist und anhand der Daten die Struktur des Netzwerks durch Vergleich verschiedener Muster ausgewählt wird, suchen constraintbasierte Ansätze nach einem Netzwerk, das sowohl die Markov Bedingung, als auch die „bedingten Unabhängigkeiten in der Wahrscheinlichkeitsverteilung“ [3] erfüllt [3].

4.1 Scorebasierte Ansätze

Scorebasierte Ansätze versuchen immer, einen Graphen zu finden, der eine Zielfunktion optimiert. Als Zielfunktion können dabei verschiedenste Scores verwendet werden. Beispiele sind hier eine Likelihood-Funktion, die einen Fit zu den Daten berechnet, das Bayes-Informations-Krieterium (BIC), das die Likelihood über alle möglichen Parametrisierungen aufsummiert oder bestrafende Ansätze, die statt der Likelihood die a-posteriori Wahrscheinlichkeit betrachten [2].

Scorebasierte Ansätze können nochmals in exakte und gierige Algorithmen unterteilt werden, wobei zweitere vor allem dann verwendet werden, wenn es sich um sehr große Graphen handelt und eine exakte Berechnung nicht mehr im Rahmen der Möglichkeiten liegt [4].

Selbst innerhalb der exakten Ansätze lassen sich die Algorithmen weiter klassifizieren. So können Branch-and-Bound-Verfahren, partial order covers oder lineare Programmierung zum Einsatz kommen [4].

B&B-Verfahren

10

Partial order covers

Verfahren mit linearer Programmierung

Ein Beispiel für gierige Ansätze ist der Greedy Equivalence Search Algorithmus von Chickering aus dem Jahre 2002 [13]. In der Regel bei einem Graph ohne Kanten startend besteht dieser Algorithmus aus Vorwärts- und Rückwärtsschritten, in denen Kanten hinzugefügt, bzw. entfernt werden. Im Zuge dessen wird bestimmt wie sich eine zu maximierende Zielfunktion durch das Hinzufügen und Entfernen der Kanten verändert. Klarer Vorteil dieses Ansatzes ist, dass er unter bestimmten Bedingungen in der Lage ist, nicht nur ein lokales, sondern sogar ein globales Optimum auszumachen [4]. Der Algorithmus kann in verschiedenen Varianten angewendet werden und es zeigt sich, dass er zum Teil an seine Grenzen geraten kann. Aus diesem Grund ist er von verschiedenen Autoren angepasst und erweitert worden ist. Ein Beispiel dafür ist die Arbeit von Alonso-Barba et. al. (2013), welche den Algorithmus in neun Abwandlungen beschreibt. Beispielsweise werden durch die Definition von Constraints die Verbindung zwischen bestimmten Zufallsvariablen ausgeschlossen, sodass der Algorithmus noch besser und effizienter auf große Netze angewendet werden kann [14]. Da es sich hierbei um constraintbasiertes Vorgehen handelt, könnten diese Abwandlungen des GES Ansatzes ebenso zu den hybriden Ansätzen gezählt werden.

Greedy Hill Climbing Algorithmus

4.2 Constraintbasierte Ansätze

Grow Shrink Algorithmus

4.3 Hybride Ansätze

Strukturlernansätze können nicht nur score- bzw. constraintbasiert sein, sondern auch Elemente beider Kategorien enthalten. Ein Beispiel für einen solchen hybriden Ansatz ist der Sparse-Candidate-Algorithmus, der in [15] beschrieben wird. Dieser Ansatz verläuft iterativ von einem leeren Graph zu einem Zielnetzwerk. Jede Iteration besteht dabei aus einem Restriktions- und einem Maximierungsschritt. Im Restriktionsschritt werden für jeden Knoten basierend auf den vorliegenden Daten mögliche Elternknoten bestimmt, wodurch die Anzahl der möglichen Netzwerke massiv eingeschränkt wird. Im Maximierungsschritt wird dann eine Zielfunktion maximiert. Es gibt für jeden der Schritte mehrere Möglichkeiten der Konzeption und Durchführung, wobei die Auswahl des Restriktionsschrittes in der Regel unabhängig von der Auswahl des Maximierungsschrittes erfolgen kann. Der Restriktionsschritt kann in einem einfachen Fall für zwei Knoten X und Y über

$$\sum_{x,y} \hat{P}(x,y) \log\left(\frac{\hat{P}(x,y)}{\hat{P}(x)\hat{P}(y)}\right) \tag{11}$$

einen nicht-negativen Wert berechnen, der durch das gemeinsame Vorkommen von Daten in X und Y steigt. Dieser Ansatz kann noch abgewandelt oder erweitert werden, soll für diese Übersicht jedoch vorerst in dieser Form genügen. Auch der Maximierungsschritt kann auf verschiedene Arten erfolgen. Beispielsweise über einen Greedy-Hill-Climbing-Algorithmus, wie er zuvor in dieser Arbeit vorgestellt wurde. Häufig kommt es jedoch noch immer zu dem Problem eines sehr großen Suchraumes, was sich durch den Einsatz von Dekompositionsansätzen verringern lässt. Hier sind beispielsweise die Separator-Dekomposition oder die Cluster-Tree-Dekomposition zu nennen. Abschließend muss sich für ein Abbruchkriterium entschieden werden. Dabei gibt es zwei Möglichkeiten. Erstens kann der Algorithmus abbrechen, wenn sich in einem Schritt im Vergleich zu einem vorherigen Schritt die Elternknoten nicht mehr ändern. Die zweite Möglichkeit ist analog dazu eine Nicht-Verbesserung des Wertes der Zielfunktion [15].

Ein weiteres Beispiel für hybride Verfahren ist der Ansatz von de Campos et al. aus dem Jahre 2009 [16]. Hier werden zunächst Constraints für Parameter und Struktur gebildet, die daraufhin in einem Branch-and-Bound Verfahren berücksichtigt werden, das eine global optimale Lösung findet. Dennoch kann das Verfahren aufgrund eines Abbruchkriteriums jederzeit abgebrochen werden und es liegt dennoch die Struktur vor, die von allen bisher getesteten Strukturen den höchsten Zielfunktionswert aufweist. Ein weiterer Vorteil ist die Möglichkeit der Parallelisierung des Algorithmus [16].

5 Lernen in ungerichteten Netzwerken

Analog zu gerichteten Bayes'schen Netzen können auch in ungerichteten Markov Netzwerken constraintbasierte oder scorebasierten Ansätze zum Lernen der Struktur angewendet werden. Auch in diesem Fall gibt es in beiden Fällen verschiedene Ansätze, die sich zum Teil deutlich voneinander unterscheiden [2].

5.1 Scorebasierte Ansätze

Das Bayes-Informationskriterium erweist sich bei Markov-Modellen als weniger nützlich, weshalb hier eher auf approximative Ansätze gesetzt wird [2].

Noch keine Beispiele

5.2 Constraintbasierte Ansätze

Noch keine Beispiele

6 Vergleich der Algorithmen

Vergleich folgt wenn Algorithmen alle abgehandelt wurden

12

7 Zusammenfassung und Ausblick

In dieser Arbeit wurde zunächst ausgehend von den Grundlagen der Wahrscheinlichkeitstheorie zu probabilistischen graphischen Modellen hingeführt. Daraufhin wurden diese Modelle klassifiziert und es wurde dargestellt, welche Möglichkeiten des Lernens in probabilistischen graphischen Modellen bestehen. Es wurde auf verschiedenste scorebasierte, constraintbasierte und hybride Möglichkeiten und Algorithmen eingegangen, über die die Struktur von Bayes'schen Netzen und Markov-Netzen synthetisiert werden kann. Das Lernen von Parametern, das in einem nächsten Schritt auf ein vorhandenes probabilistisches graphisches Modell angewendet werden kann, wurde der Vollständigkeit halber erwähnt, nicht jedoch im Detail abgehandelt, da der Fokus dieser Arbeit klar auf Strukturlernalgorithmen liegt.

Beim Vergleich der in der Literatur vorgestellten Algorithmen zeigt sich, dass viele neu veröffentlichte Ansätze nicht in all ihren Bestandteilen gänzlich neu sind. Vielmehr werden häufig bereits bekannte Algorithmen genutzt und mit einem neuen Ansatz kombiniert oder leicht abgeändert, um deren Performance zu verbessern. Es sind sowohl in der Vorgehensweise als auch in der Performance der Ansätze große Differenzen zu erkennen. Dieser Vergleich wird im Detail in Kapitel 6 gezogen.

Die Literaturrecherche zeigt zudem, dass es fundierte Werke zu den Grundlagen in Wahrscheinlichkeitstheorie und zu probabilistischen graphischen Modellen gibt. Für konkrete Strukturlernansätze ist die Literaturgrundlage allerdings recht unübersichtlich aufgebaut, weil nie in einem einzigen Paper ein zusammenhängender Überblick über Strukturlernalgorithmen und deren Verwendung und Performance erstellt worden ist. Dies wurde in dieser Arbeit versucht, aufgrund der Vielfältigkeit der Ansätze kann jedoch nicht die Vollständigkeit des Überblicks erwartet werden. Dies sollte in einer zukünftigen Arbeit nochmals in einem größeren Umfang angegangen werden.

References

1. Bishop CM (2009) Pattern recognition and machine learning, Corrected at 8th printing 2009. Information science and statistics. Springer, New York, NY
2. Koller D, Friedman N (2009) Probabilistic graphical models: Principles and techniques. Adaptive computation and machine learning. MIT Press, Cambridge, Mass.
3. Neapolitan RE (2004) Learning bayesian networks. Pearson Prentice Hall Upper Saddle River, NJ
4. Drton M, Maathuis MH (2016) Structure Learning in Graphical Modeling
5. Bosch K (2015) Großes Lehrbuch der Statistik. Walter de Gruyter GmbH & Co KG
6. Scharnbacher K (2013) Betriebswirtschaftliche Statistik: Lehrbuch mit praktischen Beispielen. Gabler Verlag
7. Bayes T (1763) LII. An essay towards solving a problem in the doctrine of chances. By the late Rev. Mr. Bayes, FRS communicated by Mr. Price, in a let-

ter to John Canton, AMFR S. Philosophical transactions of the Royal Society of London(53): 370–418
8. Borth M (2004) Wissensgewinnung auf Bayes-Netz-Mengen. Dissertation, Universität Ulm
9. Friedman N, Geiger D, Goldszmidt M (1997) Bayesian network classifiers. Mach Learn 29(2-3): 131–163
10. Pearl J (2014) Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference, 1. Auflage. Elsevier Reference Monographs, s.l.
11. Heckerman D (1995) A Tutorial on Learning With Bayesian Networks
12. Dörn S (2018) Bayes-Netze. In: Programmieren für Ingenieure und Naturwissenschaftler: Intelligente Algorithmen und digitale Technologien. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 149–181
13. Chickering DM Optimal Structure Identification With Greedy Search. In: Journal of Machine Learning Research, vol 3, pp 507–554
14. Alonso-Barba JI, delaOssa L, Gámez JA et al. (2013) Scaling up the Greedy Equivalence Search algorithm by constraining the search space of equivalence classes. International Journal of Approximate Reasoning 54(4): 429–451. doi: 10.1016/j.ijar.2012.09.004
15. Friedman N, Nachman I, Pe'er D Learning Bayesian Network Structure from Massive Datasets: The Sparse Candidate Algorithm. In: Proceedings of the Fifteenth conference on Uncertainty in artificial intelligence, pp 206–215
16. Campos CP de, Zeng Z, Ji Q Structure learning of Bayesian networks using constraints. In: ICML '09 Proceedings of the 26th Annual International Conference on Machine Learning, pp 113–120

Neuro-evolution as an Alternative to Reinforcement Learning for Playing Atari Games

Jan Niklas Kielmann

TECO, Karlsruhe Institute of Technology

Abstract. This article presents four neuro-evolution approaches, discusses their advantages and disadvantages and compares their results in the Atari domain. Specifically, conventional neuro-evolution (CNE), Covariance Matrix Adaptation Evolution Strategy (CMA-ES), NeuroEvolution of Augmenting Topologies (NEAT) and HyperNEAT are introduced. Four different state representations for Atari games are presented and evaluated. The results show that neuro-evolution can learn effective strategies for many Atari games. Algorithms using a direct encoding scheme perform the best on abstract state representations whereas an indirect encoding like HyperNEAT is needed to learn agents based on raw-pixel inputs. The algorithms partly learn fixed action sequences without taking the game state into account which is possible as Atari games are deterministic. For this reason an evaluation on random game starts is proposed which would test the generalization of the learned strategies and would also allow a better comparison with current reinforcement learning algorithms.

1 Introduction

The Atari 2600 game console was one of the first consoles released for the home market. Today it is used as a challenging reinforcement learning benchmark. The reasons for this are the simple inputs, large amount of available games, low resolution graphics and efficient emulators [3]. Goal is a learning algorithm that can learn to play different Atari games without prior knowledge and using the same set of hyperparameters for all of them.

Backpropagation-based reinforcement learning methods like DQN[15], A3C[14] and PPO[21] achieve state-of-the-art results for training agents that can play these Atari games. In many games the learned agents outperform human players. However, there are also games left were the agents are vastly inferior to their human counterpart. These are mostly games that require long term planning and have a sparse reward function like Montezuma's Revenge. For this reason it is still a very active field of research.

Evolutionary approaches for evolving neural networks, also called neuro-evolution algorithms, are a promising alternative to backpropagation-based methods [12, 20, 26]. These black-box optimization methods can deal with sparse rewards, do not need to backpropagate gradients and can handle long time horizons [20]. This article will introduce four different neuro-evolution algorithms and

present their advantages and disadvantages. Their results on different Atari games will be compare among themselves and with results of backpropagation-based approaches.

2 Neuro-evolution Algorithms

Artificial neural networks (ANN) are computational models that are inspired by biological neural networks. However, their goal is not necessarily to model the human brain as closely as possible. They consist of a number of interconnected neurons which can be represented as a directed graph. Each of these connections between two neurons has a weight assigned to it which represents the connection strength. The neurons are small computing units that usually calculate the weighted sum of their inputs and apply an activation function to calculate their output [5].

In order to solve a specific task with an artificial neural network, its weights need to be learned. There are learning algorithms that do this in a supervised fashion, like the backpropagation of errors. Here labeled training data is used to compute the error of the network and adjust the weights so that the error is minimized[19].

Evolutionary algorithms provide another method for finding the best weights of an ANN. The field of using evolutionary algorithms to evolve the weights and structure of ANNs is called neuro-evolution. The evolution of artificial neural networks requires that it is encoded into a vector of numbers, the genome. Each element in this genome vector is called a gene. The genome needs to hold all the information to create the corresponding ANN which is called the phenotype. By using a fixed topology for the network only the weights of the connections need to be encoded in the genome. However, it is also possible to evolve the network structure along with the weights. This requires a more complex encoding. These encodings can generally be categorized into direct and indirect encodings[25] (also called weak and strong representations [4]).

Direct Encoding
In a direct encoding each neuron and each connection is directly represented in the genome[4]. If the network topology is fixed and only the weights need to be encoded, each weight would be represented sequentially in the genome. This means each gene directly represents a connection weight [6].

A direct encoding that allows the evolution of the network structure needs to also encode each connection. This can be done by representing the connection matrix of the graph in the genome. However, this limits the number of possible notes, if the genome is defined to have a fixed length. It is also hard to perform crossover operations, where two genomes are combined, because the resulting genome must still represent a valid network [25]. For example the resulting network should not contain sub-networks that are not connected to the rest of the neurons.

Indirect Encoding
An indirect encoding does not specify each neuron and connection separately. Instead it only specifies rules that can be used to construct the neural network. For example these rules can simulate cell division [8]. This allows large networks to be encoded in a compact way. However, the indirect encoding also implicitly restricts the set of possible network structures, which might not include the optimal solution [25].

A neuro-evolution algorithm typically starts out with an initial set of random networks, each encoded into a genome. This set is called the initial population and is iteratively optimized. In each iteration, also called generation, the networks are evaluated using a fitness function which ranks the performance of the network. For instance, this could be the score reached in a game. Networks with low fitness scores get discarded. Only the fittest individuals in the population survive and get to reproduce. In this context reproduction means that two networks are be combined in a process called crossover. The resulting networks created during this reproduction phase are called the offspring. Moreover random mutations are applied to the genomes of the current generation. After some iterations this process leads to neural networks that reach a high fitness score.

In the following sections four neuro-evolution algorithms will be introduced. Conventional neuro-evolution is the least complex one. It was chosen as a baseline to test whether the more advanced techniques used by the other algorithms provide a benefit in the Atari domain. The CMA-ES algorithm is a wildly used optimization algorithm for non-convex optimization problems. It was selected because it is not specific to neuro-evolution and has been used to solve many other problems. It represents a set of algorithms that only evolve the network weights and do not use any methods that are specific to the evolution of networks. The NEAT algorithm was chosen as it is a well known neuro-evolution algorithm that successfully evolves the network structure along with the network weights. It is used to test the hypothesis that the evolution of the network structure provides a benefit over more general algorithms like CMA-ES. Lastly, the HyperNEAT algorithm is used as a representative of indirect encoding neuro-evolution algorithms.

2.1 Conventional neuro-evolution

The term conventional neuro-evolution is not clearly defined. Here the definition of Hausknecht et al.[12] will be used. They describe it as a neuro-evolution algorithm that only optimizes the network weights and uses a fixed network topology. A direct encoding for the network weights is used and common crossover and mutation operators are applied to it.

The crossover operator describes how two genomes in the current population are combined to create a new individual for the next population. There are several different techniques which can be seen in Figure 1. In the single-point crossover one point in the genomes is chosen at random after which the two genomes are swapped. In the double-point crossover two such points are selected

and two swaps are performed [13]. For the uniform crossover the genes are chosen randomly from either the first or second parent [27].

In addition to a crossover the offspring is also randomly mutated by a mutation operator. As with the crossover operator there are many different options. One common operator is the uniform mutation operator which selects a few genes with a small probability and replaces their values with a new values drawn from a uniform distribution [11, 13]. Another popular operator is the Gaussian mutation operator which adds random Gaussian noise to each gene. The mean of the Gaussian distribution is set to 0 so that most genes stay almost the same. The standard deviation must be determined empirically or can be part of the genome which allows it to be adapted by the evolution as well [2].

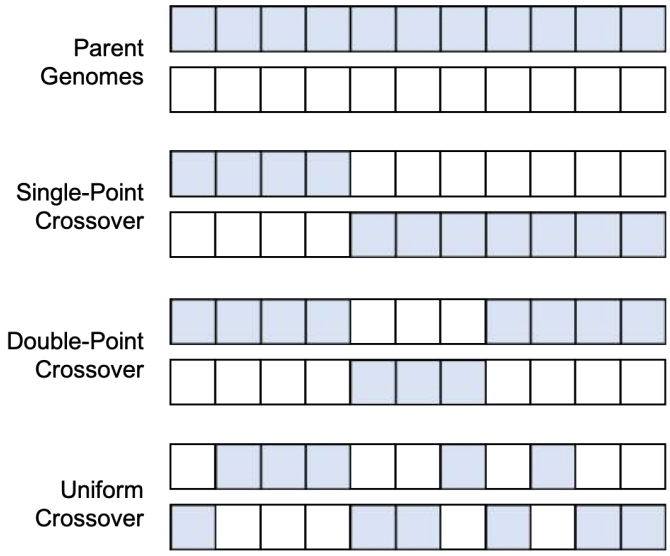


Fig. 1. Common crossover operators. The first row shows the two parent genomes chosen for reproduction. The other three rows show two genomes that could result from the respective crossover operator. Image created by author.

Hausknecht et al.[12] argue that networks evolved with this conventional neuro-evolution algorithm can find high performing ANNs given enough time because each weight can be fine-tuned independently.

Advantages	Disadvantages
• Very simple and straight forward to implement. • Low complexity makes parallelization easy and allows to scale up to many CPUs. • Can achieve very good results when used at large scale.	• Only network weights are learned. A good network architecture must be chosen beforehand. • Multiple runs with different architectures needed. • Can be slow to converge because no advanced techniques are used to adjust the steps size and direction.

2.2 CMA-ES

The Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) is a stochastic method for continuous parameter optimization of non-linear, non-convex functions. It can be used to evolve the weights of a fixed topology neural network that optimizes a complex fitness function. The main idea is to use a multi-variate normal distribution to generate the population by sampling from it. The parameters of the distribution are then updated based on the fittest individuals in the generated population [12]. In each iteration of the algorithm the following steps are executed [10]:

1. Sample λ genomes from the distribution $\mathcal{N}(m, C)$ where m is the mean and C the covariance matrix of the multivariate normal distribution
2. Create ANNs for all λ genomes and evaluate their fitness
3. Choose μ individuals with the highest fitness
4. Update the mean m using the fittest μ individuals
5. Update the covariance matrix C using the fittest μ individuals

Mean Update
The goal of the mean update is to move the mean closer to the genomes that performed well. In the next generation this will cause more samples to be taken from this region. The CMA-ES algorithm sets the new mean m' to the weighted average of the μ fittest individuals:

$$\mathbf{m}' = \sum_{i=1}^{\mu} w_i \mathbf{x_i}$$

$$\sum_{i=1}^{\mu} w_i = 1, \quad w_1 \geq w_2 \geq \ldots \geq w_\mu > 0$$

where
$\mathbf{x_i}$ is the i-th genome in the population sorted by fitness.
w_i is the weight of the genome $\mathbf{x_i}$.

All weights are greater than 0 and sum up to 1. They are usually chosen in a way that assigns the highest weight to the fittest individual and reduces the weight linearly for the other individuals (e.g. $w_i \propto \mu - i + 1$) [10].

Covariance Matrix Update
The covariance matrix should be updated in a way that biases the sampling of the next population towards the direction of the most successful individuals of the last generation [12]. The original covariance matrix that was used to create the population, can be estimated using the sample covariance matrix [18]:

$$C_{sample} = \frac{1}{\lambda - 1} \sum_{i=1}^{\lambda} (\mathbf{x_i} - \frac{1}{\lambda} \sum_{j=1}^{\lambda} \mathbf{x_j})(\mathbf{x_i} - \frac{1}{\lambda} \sum_{j=1}^{\lambda} \mathbf{x_j})^T$$

In order to compute a better covariance matrix only the best μ individuals are used and weighted. This is similar to the weighting of the mean update. Moreover CMA-ES uses the true mean m that was used to create the population instead of the mean calculated on the sampled population [10]:

$$C_{\mu} = \frac{1}{\mu} \sum_{i=1}^{\mu} w_i (\mathbf{x_i} - m)(\mathbf{x_i} - m)^T$$

This update rule estimates the variance of the step size $x_i - m$ instead of the variance within the sampled population [10]. Figure 2 shows that this update method leads to a higher variance in the direction of better performing individuals. This enables CMA-ES to make bigger steps in the right direction when the best solutions are far away and narrow the search space when the best solutions are close to the mean. [9]

One drawback is the run time of $\mathcal{O}(n^2)$, where n is the number of genes in the genome, due to the calculation of the covariance matrix [10]. This can be problematic for the evolution of ANNs which can have a large number of weights.

Advantages

- Fast convergence due to the adaptive step size
- Empirically successful in many applications [10].
- Can deal with non-convex and noisy objective functions which is the case for optimizing ANNs
- Very few hyperparameters
- Rigorous mathematical derivation

Disadvantages

- Just like the conventional neuroevolution only the weights are learned. A human expert has to choose a network architecture beforehand.
- Large ANNs with high-dimensional inputs like images can not be evolved due to the large computational complexity.

2.3 NEAT

NeuroEvolution of Augmenting Topologies (NEAT) is a method that allows to evolve the structure and weights of an artificial neural network simultaneously. It has been successfully applied in numerous domains like robot control[25], video games[12, 23] and even physics[1]. When evolving the structure along with the weights, Stanley and Miikkulainen[25] identified three main challenges:

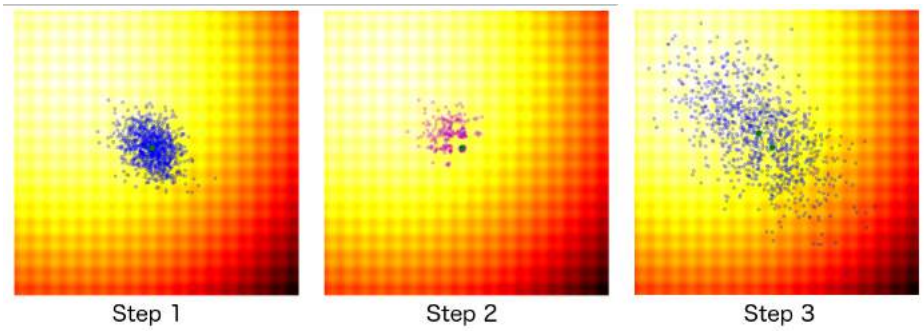


Fig. 2. Mean and covariance update. This figure shows one evolution step of the CMA-ES algorithm on a non-linear fitness function. Brighter values represent a higher fitness score. The first step shows the sampled population as blue dots. The mean of the distribution that was used for the sampling is shown as a green dot. In step two only the top 25% of the population are selected and used to calculate the mean and covariance update. Step three shows the next population that was sampled from the updated distribution. It is visible that the variance in the direction of the best performing individuals has been increased. Image source [9]

1. How can the topology and weights of the network be encoded, so that a crossover between two structurally different networks is possible in a meaningful way?
2. How can new innovative changes in the topology be protected, even if they have a lower fitness score in the beginning.
3. How can the network topology be kept as small as possible throughout the evolutionary process without the need of a fitness function that explicitly rewards smaller networks.

The NEAT Algorithm solves these problems through the use of an direct encoding with historical markers, specification and iterative evolution of simple structures.

Encoding

The encoding scheme of the NEAT Algorithm contains a list of neurons and a list of connections between those neurons. Each connection is described by its start and end neuron, its weight, a flag that indicates if the neuron is enabled and an innovation number. This innovation number is a unique id that the connection got assigned when it was created. Figure 3 shows an example genome and the ANN it represents.

There are two kind of mutations that can be applied to this genome. Firstly a new connection between two existing nodes can be added. To do this, a new entry is added to the connection list which is initialized with a random weight and a new unique innovation number. Secondly a new node can be added, by splitting an existing connection and inserting the new node in between. The

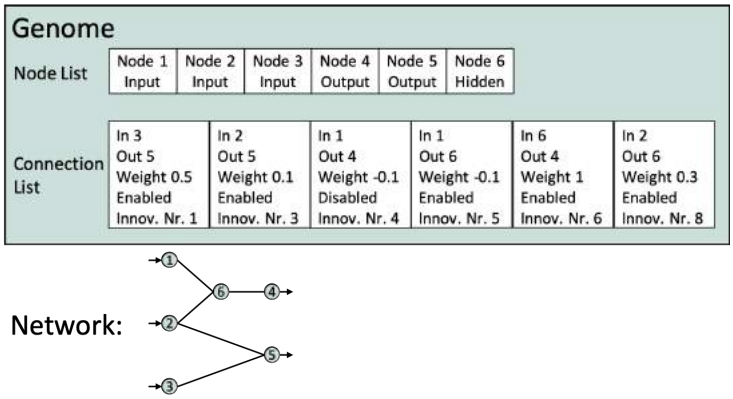


Fig. 3. Encoding scheme of NEAT Algorithm. The Genome consists of a node list and a connection list. This example genome describes a ANN with three inputs, two outputs and one hidden neuron. Image inspired by [25]

old connection stays in the genome but gets disabled. The two new connections are added to the end of the connection list and both receive a new innovation number. The weight of the old connection is assigned to the connection leading to the new node. The other new connection is initialized with a weight of 1 [25].

Crossover

When performing a crossover of two artificial neural network, one of the main challenges is the competing conventions problem. It means that there are multiple ANNs that represent the same solution. For example the position of the neurons in a hidden layer can be changed around without changing the calculation the network performs. If these different networks that represent the same solution result in a differently encoded genome, then a crossover can not be performed in a meaningful way.

This problem is even more present when the genome can represent different network topologies. There are many artificial neural network with differing topologies that compute the same solutions. Their encodings can differ in length and genes at the same position in the genome might represent completely different traits whereas genes expressing the same trait may be located in different places in the genome. A trait is a specific characteristic of the neural network like a specific neuron that detects horizontal lines in an image. Some mechanism is needed that aligns two genomes so that genes that represent similar traits overlap. This allows a crossover which does not destroy the function of the network [25].

The NEAT Algorithm uses the innovation numbers of the connection to perform this alignment (see Fig. 4). They serve as historical markers that describe the origin of the connections. When performing crossover of two genomes in NEAT, the genes with the same innovation number are aligned. These genes are called matching genes. For each of these matching gene pairs it is decided

randomly which gene is kept in the resulting offspring genome. The remaining genes which do not have a corresponding gene in the other genome are either called disjoint genes when they occur in the middle of the gene string or excess genes when they appear at the end of the genome. The disjoint and excess genes are only inherited from the more fit parent. This process of aligning genes using historical markers is similar to a biological process called synapsis where the RecA protein lines up matching genes [25]. By using historical markers the NEAT Algorithm ensures that no genes that have the same origin are duplicated or both removed.

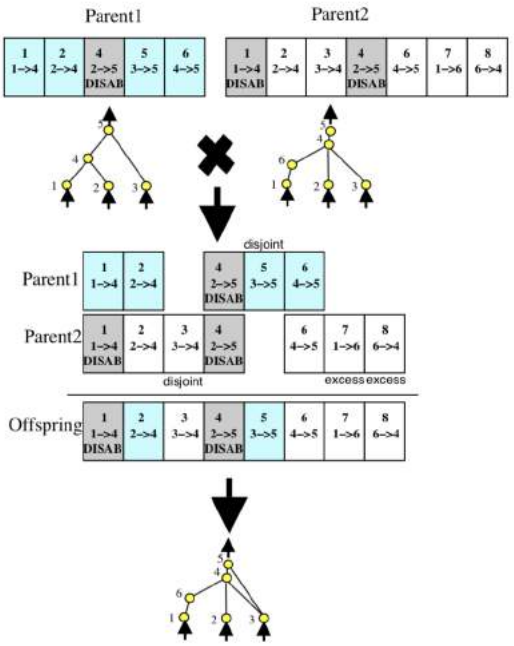


Fig. 4. Crossover using innovation numbers to align genomes. The two parent genomes look differently and represent different network topologies. By using the innovation numbers as historical markers the genes that have the same origin can be lined up. This way a new network that is a combination of both parents can be created without the need for a topological analysis. Image source [25]

Protecting Innovation

Innovations occur during the evolution when new neurons get added to the network and its structure is changed. These innovations might lead to a network that is better fit for the task it needs to handle. However, it is unlikely that the new randomly inserted neuron immediately provides a benefit. A few optimization

steps will be needed before a performance increase can be observed. Most of the time an innovation will cause the fitness score of the individual to decrease. Because of that, most innovations will not stay in the population for long enough which makes it impossible for complex network structures to emerge during the evolution. Therefore innovations need to be protected, so new structures get time to be optimized.

NEAT uses speciation to solve this problem. Genomes which represent Networks with a similar structure and weights belong to the same species and only the individuals in the same species compete against each other. This requires a measure that describes the similarity of two networks. In NEAT this is done with the compatibility distance which is defined as:

$$\delta = \frac{c_1 E}{N} + \frac{c_2 D}{N} + c_3 * \overline{W}$$

The historical markers are used to compute the number of excess genes E and disjoint genes D. $\overline{W}$ is the average weight distance of matching genes. The factor N is the length of the genome and is used to normalize the number of excess and disjoint genes. All three terms are scaled by a coefficient c1, c2 or c3. They allow to adjust the balance between the three factors [25].

This compatibility distance can now be used to sort the population into species. For that a list of species is maintained, each with one random representative from the last generation. A genome of the current generation is placed into a species if its compatibility distance δ with the representative is lower than some threshold δ_t. In the case that a genome is not compatible with any existing species, a new species with this genome as its representative is created [25].

To determine which individuals are allowed to reproduce explicit fitness sharing is used. The number of offspring a species produces is proportionally to the average fitness of this species. The best performing genomes in each species are mutated and recombined by crossover. The offspring replaces all individuals in the species [25]. This ensures that each species is allowed to create some new individuals for the next generation even if the performance of the species is lower than that of the others.

Minimizing the Topology

Stanley and Miikkulainen[25] argue that it is desirable to find networks with as few neurons as possible. This minimizes the dimensionality of the weight space that needs to be searched. Many neuro-evolution algorithms start out with a population of random topologies. This, however, leads to unnecessarily complex network structures. NEAT, on the other hand, starts out with a set of minimal Networks that contain no hidden units. This way only structural changes that provide a benefit will survive the selection process and the algorithm is biased towards minimal solutions. This process does not need an additional term in the fitness function for penalizing bigger networks which would require another hyperparameter.

Advantages	Disadvantages
• The network topology and weights are evolved simultaneously • Efficient crossover between networks with differing topologies by using historical markers • Innovation in the population is protected through speciation • Network size is minimized by starting from population with no hidden units. This reduces overfitting as the network is just big enough for the problem.	• The direct encoding makes it hard to evolve networks for high dimensional inputs like images • To recognize repeating patterns and symmetries in the input data, the same structures and weights need to be learned multiple times.

2.4 HyperNEAT

The NEAT algorithm allows the evolution of the network topology and weights simultaneously. The resulting networks are far smaller than the neural networks in the human brain they are modeled after. Moreover the generated networks are far less organized than their biological counterpart which has patterns that repeat throughout its structure [24].

The direct encoding of the NEAT algorithm makes it hard to evolve networks with many neurons. Repeating patterns would need to evolve independently from scratch each time. For this reason Stanley et al.[24] propose an indirect encoding scheme called *connective Compositional Pattern Producing Networks* (connective CPPNs).

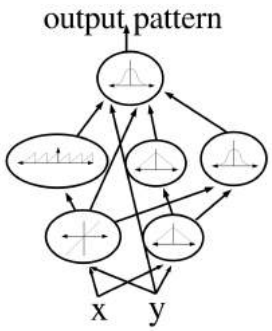


Fig. 5. CPPN graph representation. The CPPN connects different functions together in order to compose a complex function. Each connection in the graph has a weight and each node calculates the weighted sum of its inputs and applies its activation function to it. Image source [22].

Compositional Pattern Producing Networks
CPPNs are networks that are composed of a set of simple functions. Similarly to ANNs they can be represented as a graph like shown in Figure 5. Each node computes a weighted sum of its inputs but in contrast to a regular ANN each node can use a different activation function [22].

A CPPN with two inputs and one output can be visualized as a gray-scale image. For each pixel in the image the x and y coordinate is fed into the CPPN and the resulting value is interpreted as the intensity of this pixel. In Figure 6 some example images generated by an CPPN can be seen. The resulting patterns can have symmetries by using symmetric functions like a Gaussian or include repetitions by using periodic functions like a sine wave [22].

ANNs from CPPNs
In order to create an ANN from a CPPN the neurons of the ANN are placed on a 2D grid. A CPPN with 4 inputs and one output is used. The inputs represent the coordinates of two neurons on the grid. The resulting output is used as the weight between the two neurons that were used as the input. To construct the complete ANN the CPPN is evaluated for each pair of neurons on the 2D grid. If the resulting weight is higher than some fixed threshold, then a connection with this weight is created. These CPPNs that are used to generate a ANN are called connective CPPNs and the connectivity patterns they produce are called substrate. Because CPPNs are able to produce symmetric and repeating patterns, the generated ANNs also show these patterns. Moreover a single CPPN represents a continuous function and can therefore be used to create ANNs at different resolutions. To increase the resolution only the amount of neurons on the grid needs to increased and the connections need to be queried from the CPPN again.

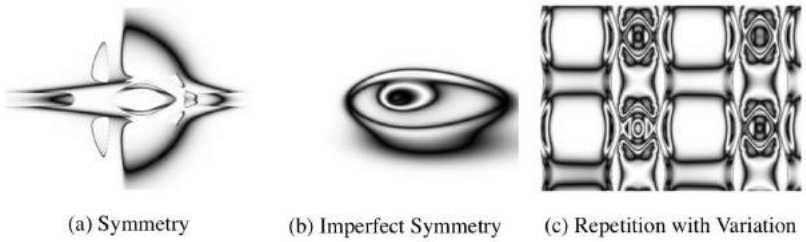


Fig. 6. Patterns generated by a CPPN. The CPPN is evaluated for each pixel and the output is interpretet as pixel intensity. The patterns show symmetries and repetition caused by the use of symetric and periodic activation functions. Image source [22].

Substrate Configuration
The previous paragraph stated that the neurons of the ANN are placed on a 2D grid. However, it is also possible to use other layouts. These layouts are called substrate configurations. For example a 3D grid can be used to layout the neurons. This would require a CPPN with six inputs, as the position of one neuron is now specified by three coordinates. The substrate layout is not limited to grid structures. For example it is possible to arrange the neurons in concentric circles. The neurons can be referenced using polar coordinates.

In addition to the substrate configuration the input and output neurons must be defined. On a 2D grid the top row could be input neurons and the bottom row the output neurons. All neurons in between would be hidden units. Choosing a substrate configuration and the layout of input and output neurons is application dependent. The goal is to model the geometry of the problem. For example in the case of image classification it makes sense to place the neurons on a 2D-grid, as neighbouring pixels contain related information. However, if the task is to control a round robot that can freely move on a 2D plane and has touch sensors in all directions, then it would be best to layout the neurons corresponding to the sensors in a circle to match the real world geometry of the robot.

CPPN evolution
ANNs and CPPNs are structurally very similar. This means the NEAT algorithm can be used to evolve them with a few teaks. The NEAT encoding for the nodes receives an additional field that specifies the used activation function. Furthermore, the compatibility distance function that is used for the speciation is adjusted to take differing activation functions into account. The total number of activation functions that are different in the two genomes is counted and added as a further weighted term to the compatibility distance function. This causes individuals with differing activation functions to form separate species [22].

The HyperNEAT algorithm can be summarized by the following steps [24]:

1. Choose a layout for the neurons (substrate configuration) and define the input and output neurons.
2. Initialize a population with minimal CPPNs with random weights. They are encoded using the NEAT encoding scheme.
3. Iterate for N generations or until solution is found:
   (a) For each CPPN in the population do:
      i. Evaluate the CPPN for each possible connection between neurons. If the resulting output exceeds a threshold, a new connection is created with a weight set to the output.
      ii. Run the resulting ANN in the task domain to obtain its fitness score.
   (b) Reproduce the CPPNs through mutation, crossover and speciation according to the NEAT algorithm described in Section 2.3.

Advantages

- The network topology and weights are evolved simultaneously
- The indirect encoding allows to evolve networks with high dimensional inputs
- ANNs generated by CPPNs contain symmetries and repetitions
- Knowledge about the problem geometry is incorporated by choosing the substrate configuration
- One evolved CPPN can be used to generate ANNs for any desired input resolution

Disadvantages

- The indirect encoding makes the algorithm more complex and for inputs with a low dimensionality the simpler NEAT algorithm often outperforms HyperNEAT
- Choosing the right substrate configuration requires domain knowledge and experience

3 Atari Research Environment

The Atari 2600 was the first popular home video game console. It was released in 1977 and over the time over 1000 games were created for the system [17]. This was possible through the use of a general purpose CPU, which allowed the game code to be stored on cartridges separate from the console hardware [3]. This large amount of available games is one reason for using Atari games as a benchmark for learning algorithms. It allows an algorithm to be designed and tested on a subset of these games and test its generalization abilities on the remaining games.

Moreover the 1.19Mhz CPU used by the Atari 2600 is not very powerful compared to modern processors. Because of this many Atari games can be simulated in parallel and the simulation speed is significantly higher than on the original console. This is another reason for using Atari games as a research environment. Most learning algorithms need to simulate the game many times before learning a useful strategy. There are already many emulators like the "Stella"[1] emulator. Frameworks like "OpenAI Gym"[2] and the "Arcade Learning Environment"[3] provide a layer on top of these emulators and allow learning algorithms to interface with the games.

Another advantage is the small action and state space of Atari games. The controller of the Atari 2600 consists of a single button and a joystick that can be in 9 different states (middle, up, down, left, right, up-left, up-right, down-left, down-right). This results in 18 distinct input combinations the agent can choose from. The observable state space consists of the 160×210 pixel values (up to 128 possible colors) and basic sound effects. This keeps the search space for possible policies small enough to be explored by learning agents while still

[1] https://stella-emu.github.io/
[2] https://gym.openai.com/
[3] https://github.com/mgbellemare/Arcade-Learning-Environment

allowing interesting and complex games. These games have interesting game dynamics but are limited to a small 2D world with few agents.

Fig. 7. Left: The Atari 2600 video game console. Right: Screenshots of 8 different Atari games. They show the simple, low resolution graphics of the Arari 2600.
https://upload.wikimedia.org/wikipedia/commons/b/b9/Atari-2600-Wood-4Sw-Set.jpg
https://atariage.com/images/query_headers/Atari2600_Screenshots_Header.jpg

3.1 State Representation

Raw Atari frames are 210 x 160 pixel images with 128 unique colors. This high dimensional input space is computationally demanding and requires large neural networks with many parameters. For this reason different representations of the game state are used that have varying levels of abstraction.

Object Representation
This is the most abstract state representation using the least general features. A template based object detector is used to extract the position of different objects on the screen. The objects are categorized in classes like enemy or player. A human has to extract the sprites of these objects and sort them into the correct class. At run-time the extracted sprites are compared with the contents of the screen to detect the objects. For animated sprites multiple images are extracted. This means the algorithm does not need to learn the pixel representation of the objects and the category they belong to. At the same time, however, this also means that algorithms using the object representation are the least general, as they require human knowledge to extract relevant objects. To reduce the input dimensionality the object positions are represented on a scaled down 8 x 10 gird [12].

8-Color Pixel Representation
This state representation directly encodes the pixels visible on the screen. To reduce the dimensionality of the input, the 8 color mode of the Atari is used instead of the default 128 color mode. By only using 8 colors the different objects are easier to distinguish. With a screen resolution of 210 x 160 pixel this would still lead to $210 * 160 * 8 = 268800$ input neurons. To further reduce this number, the input is down-sampled to 21 x 16 pixels which results in only 2688 input neurons [12].

This raw-pixel representation is more general than the object representation and mirrors what a human would see [12]. Nevertheless, it is a very simplified version of the game screen. By using only 8 colors, one color often corresponds to a specific object type which makes this representation similar to the segmentation used in the object representation.

Gray-scale Representation
For this state representation the 128 color mode of the Atari is used. Instead of using the color information directly a screen-shot for each frame is created which is in the RGB format. This RGB image is then transformed to a gray-scale image. To reduce the input dimensionality it is down-sampled to 110 x 84 and then cropped into a 84 x 84 image. The last four frames are preprocessed in this way and then stacked together. This forms a 84×84 x 4 image that is used as the input for the learning algorithm [15, 16].

The gray-scale state representation is the most general representation of the ones presented here, as it uses the full 128 colors of the Atari and operates on a comparably high resolution. The history of four frames allows the learning agent to predict the movement of objects on the screen. A learning algorithm needs to learn a reliable object detector in addition to the policy for playing the game.

Noise-Screen Representation
The noise-screen representation consists of a vector with random seeded noise. This noise is completely uncorrelated to the state of the game. For a human it would be hopeless to achieve a high score with this representation. However, Atari games are deterministic so a learning agent can learn a specific sequence of action that will perform well. For this the game state is not needed [12].

This representation is used as a baseline to investigate how much of an algorithm's success is based on pure memorization of the optimal action combination and how much on the understanding of general concepts which are extracted from the game state [12].

3.2 Network Architecture for Atari

The neuro-evolution algorithms described in Section 2 can be used to learn a strategy for playing an Atari game. Hausknecht et al.[12] define possible network topologies for the object representation, 8-color pixel representation and noise-screen representation. The conventional neuro-evolution and CMA-ES need the

complete network topology, whereas for NEAT and HyperNEAT only the inputs and outputs must be defined. Generally a network with three layers is used: an input layer which contains the game state representation, a hidden layer which learns an internal representation of the game state and an output layer.

The output layer consists of a 3×3 matrix of neurons (see Fig. 8) and a single neuron for the fire button. This geometric representation of the output layer is only needed for the HyperNEAT algorithm. The network for the other algorithms contains one output neuron for each valid action. There are 18 possible actions (9 joystick positions in combination with the fire button) but not all of them are valid for every game. For example actions that restart the game are excluded [12].

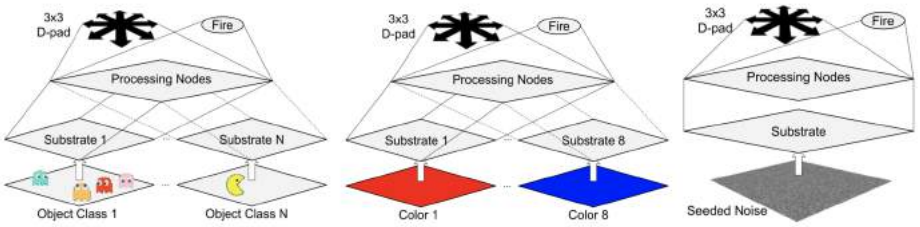


Fig. 8. HyperNEAT network architectures. Input and output configuration for the object, 8-color pixel and noise-screen representations. For other algorithms than HyperNEAT the input and output layers are not geometrically placed on a plane. Image source [12].

The input layer depends on the used state representation. For the object representation a plane with 10 × 8 neurons is used for each object category. This way each neuron is mapped to a region of the screen. When an object is visible on the game screen the corresponding neuron for that region in the plane for that object category is activated. Similarly for the 8-color pixel representation there are 8 planes with 21 × 16 neurons. If a color is visible in the region a neuron is mapped to, this neuron will be activated. A network using the noise-screen representation has one plane of input neurons which will be activated randomly but with a fixed seed.

For the gray-scale state representation this network topology has to many parameters because of the high input dimensionality. For this reason a Convolutional Neural Network (CNN) is used, as it reduces the number of parameters by using weight sharing and provides a way to learn translation independent filter kernels[7]. The CNN used by Mnih et al.[16] for this representation, which is also used by others, receives as input the 84 × 84 × 4 image created by the preprocessing. The first hidden convolutional layer consists of 32 8 × 8 filters with stride 4. The second hidden layer convolve 64 4 × 4 filters with stride 2. The third convolutional layer consists of 64 3 × 3 filters with stride 1. The last hidden layer is fully-connected and has 512 neurons. Each of the hidden layers

uses ReLu as activation function. The output layer consists of one neuron for each possible action (up to 18).

4 Results

4.1 Neuro-Evolution Results

First the results of Hausknecht et al. [12] will be presented. They evaluated the conventional neuro-evolution, CMA-ES, NEAT and HyperNEAT algorithms on the object, 8-color pixel and noise screen representation. They do not report results on the gray-scale representation, although it has now become the standard state representation for this research field. In their experiments each episode starts from the beginning of the game. This way the starting conditions for each episode are the same and a deterministic sequence of actions can be learned. After 50,000 frames which corresponds to about thirteen minutes of game time the episode is terminated and the reached score is used as the fitness value for the agent. Figure 9 shows the results of the algorithms on 61 Atari games after 150 generations with a population size of 100. To make the score of the different games comparable and create a single score for the performance of an algorithm on all games a z-score normalization is used. It is defined as:

$$\text{z-score} = \frac{\text{score} - \mu}{\sigma}$$

where μ is the mean and σ is the standard deviation of the scores of all algorithms on one game. A z-score of 2 would mean that the achieved score is two standard deviation above the mean of all algorithms. Computing the mean z-score over all games allows a comparison of the relative performance of all evaluated algorithms [12]. However, this normalization also makes it hard to compare the scores with other results. For example by adding new algorithms that perform poorly the z-score of the other algorithms is increase.

The evaluated algorithms perform best on the object representation. It provides the highest level of abstraction and therefore the smallest state space dimensionality. With the noise screen representation the algorithms did not reach the performance of the object representation. This means the evolved networks do not only learn a fixed sequence of actions but also learn higher level concepts on the screen that they react to [12]. Nonetheless, the score reached with the noise screen is still high and in some games it even is the best performing state representation.

Although HyperNEAT can incorporate geometric information and repeating patterns in its indirect encoding it did not significantly outperform the other algorithms. Instead the NEAT algorithm has the highest mean z-score with both the object and noise representation. This suggests that the evolution of the network topology provides an advantage and many Atari games can be learned with relatively simple networks like the ones produced by NEAT [12].

For the 8-color pixel representation only HyperNEAT could be used to evolve a successful ANN. This is because of its indirect encoding which can efficiently

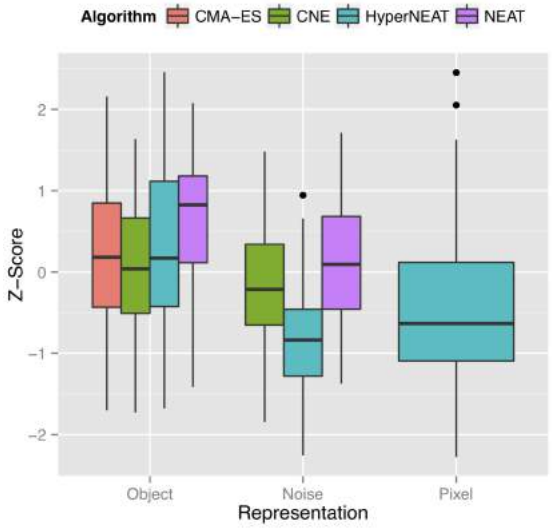


Fig. 9. Neuro-Evolution results. Boxplots of the mean Z-scores of the neuro-evolution algorithms on 61 Atari games with different state representations. Missing boxplots mean the algorithm was computationally intractable for the specified state representation. Image source [12].

encode large networks and is independent of the input resolution. The other algorithms use a direct encoding which results in a very large genomes as the network for the 8-color pixel representation has 2688 input nodes. This results in ANNs with over 900000 weights. Running the forward pass of these networks is still possible but the crossover and mutation operations are to computationally expensive [12]. HyperNEAT has a lower score using the 8-color pixel representation than with the object representation but still beats the noise-screen representation. This implies that the ANN evolved by HyperNEAT started to extract useful information from the pixel representation.

4.2 Backpropagation-Based Reinforcement Learning Results

In this section the results of the neuro-evolution algorithms are compared to backpropagation-based reinforcement learning methods. Mnih et al.[15] report results of their DQN method and compare it with HyperNEAT. DQN uses the gray-scale representation which is the most general one. For HyperNEAT results with the object and 8-color pixel representation are reported. Table 1 shows that DQN outperforms HyperNEAT in all seven tested games except for Space Invaders. This could mean that DQN generally performs better although it uses a more abstract state representation. However, only a small subset of the available games is used.

More recent reinforcement learning algorithms were evaluated on the same set of games as HyperNEAT. However, the setup used for these experiments differs

	HyperNEAT Object	**HyperNEAT 8-color**	**DQN Gray-Scale**
B. Rider	3616	1332	**4092**
Breakout	52	4	**168**
Enduro	106	91	**470**
Pong	19	-16	**20**
Q*bert	1800	1325	**1952**
Seaquest	920	800	**1705**
S. Invaders	**1720**	1145	581

Table 1. Scores of HyperNEAT and DQN on seven Atari games. Source [15]

in three main ways from the setup used by Hausknecht et al. which makes it difficult to compare the reported scores. Firstly the episodes are capped at 18000 frames which corresponds to about 5 minutes of in-game time instead of 50000 frames (13 min). A longer game time gives the agent more time to collect points as long as it does not die. Secondly the more recent publications do not start the game from the beginning but instead perform 30 random actions at the start of the game or sample starts from a recorded human play session. This way the initial game state is not fixed and the agent cannot learn a fixed sequence of actions. This makes it harder for the learned agent to achieve high scores but the agent learns more general game concepts. Thirdly Hausknecht et al. use the object, 8-color pixel and noise-screen representations whereas more recent results are obtained using the gray-scale representation which is more general and harder to achieve good scores with. For this reason the neuro-evolution algorithms would need to be reevaluated with this new experiment setup in order to compare the results.

However, there are recent results by Such et al.[26] that suggest that neuro-evolution can achieve similar performance to reinforcement learning even under these harder experiment conditions. They use a conventional neuro-evolution algorithm to evolve a deep convolutional neural network with over 4 million parameters. To evolve such a massive network the algorithms is heavily parallelized. In future work it would be interesting to see if neuro-evolution algorithms like HyperNEAT can be scaled to a similar level of parallelization and evolve the network topology together with the weights. For this a very efficient encoding must be found in order to reduce the communication overhead of the parallelization.

5 Conclusion

This article presented four different neuro-evolution approaches, highlighted their advantages and disadvantages and summarized their performance on Atari 2600 games. For this four possible representations of the Atari game state were introduced.

The conventional neuro-evolution algorithm is simple to implement and can easily be parallelized but only optimizes the network weights and has no mechanisms in place to achieve a faster convergence.

CMA-ES is a wildly used method for solving black-box optimization with an adaptive step size and few hyperparameters. However, it also only evolves the network weights and can be computationally expensive for high-dimensional inputs.

The NEAT algorithm allows the evolution of the network topology along with the weights. It does so by starting out with a minimal network topology which makes sure that the found network is as small as possible. Nonetheless, for very large inputs the direct encoding used by NEAT becomes inefficient and repeating patterns in the network need to be independently evolved multiple times.

HyperNEAT addresses the problems of NEAT by using an indirect encoding scheme based on CPPNs. This allows the efficient evolution of very large networks with repeating patterns. This added complexity does, however, lead to worse performance for low-dimensional input problems where NEAT usually outperforms HyperNEAT.

The results published by Hausknecht et al. showed these neuro-evolution algorithms are able to evolve successful networks for playing Atari games. The learned strategies beat human players in three games and discovered opportunities for infinite scores in three more games [12]. Direct encoding algorithms like NEAT and CMA-ES performed better than the indirect encoding of HyperNEAT on low-dimensional input representations like the object and noise-screen representation. NEAT was able to achieve higher scores than the other direct encoding methods, suggesting that the evolution of a minimal network topology provides an advantage over fixed topology networks. HyperNEAT was the only algorithm capable of learning based on the 8-color pixel representation. Here the indirect encoding enabled the evolution of large networks with repeating structures which are needed for dealing with high-dimensional state representations.

The learned agents often exploit a fixed sequence of actions that are hard to reproduce by human players. Agents trained using the noise-screen representations still achieve comparably high scores. This means the agent learns to play the game without any information about the game state. This only works because Atari games are deterministic and the episodes always start at the beginning of the game. In future work it would be interesting to evaluate these neuro-evolution algorithms on random starts. This can be done by performing a number of random actions at the beginning of the game or by choosing a random game state from a recorded human play session. This way the evolved network must react to the objects on the screen and it would not be possible to achieve a good performance with the noise-screen representation.

Mnih et al.[15] showed that the DQN reinforcement learning algorithm outperforms HyperNEAT in some games. However, only the results on a small subset of games were reported. A more detailed comparison of the results of neuro-evolution and reinforcement learning algorithms would require experiments performed in the same conditions. In particular the neuro-evolution algorithms would need to

be evaluated on random starts and the gray-scale state representation. For this scaled up versions of the presented neuro-evolution algorithms utilizing heavy parallelization would need to be developed similar to the results of Such et al.[26].

6 Outlook

There is evidence that the performance of neuro-evolution algorithms can be greatly increased by scaling them up to run on big computer clusters[26]. Because no gradients need to be calculated and exchanged between all computing nodes, neuro-evolution algorithms are easy to parallelize. Using a simple conventional neuro-evolution algorithm Such et al.[26] were able to achieve promising results on the Atari domain. A future research topic would be to answer the question if more advanced algorithms like NEAT could also be scaled up in a similar fashion to further increase the performance.

Another idea for further research would be to adapt NEAT to evolve CNNs instead of simple feed forward networks. CNNs have the advantage that they can deal with high dimensional inputs like images by finding translation invariant patterns. The direct encoding of the NEAT algorithm would need to be adapted to include parameters like kernel size and the number of feature maps which would be evolved by the algorithm together with the weights.

Lastly, hybrid approaches of neuro-evolution and backpropagation based solutions could be tried out. Evolution would be used to find the best network topology whereas backpropagation would be used to learn the weights. This way the the strengths of both methods could be combined.

References

1. Aaltonen, T., Adelman, J., Akimoto, T., Albrow, M., González, B.A., Amerio, S., Amidei, D., Anastassov, A., Annovi, A., Antos, J., et al.: Measurement of the top-quark mass with dilepton events selected using neuroevolution at cdf. Physical review letters 102(15), 152001 (2009)
2. Bäck, T., Schwefel, H.P.: An overview of evolutionary algorithms for parameter optimization. Evolutionary computation 1(1), 1–23 (1993)
3. Bellemare, M.G., Naddaf, Y., Veness, J., Bowling, M.: The Arcade Learning Environment: An Evaluation Platform for General Agents. Journal of Artificial Intelligence Research 47, pages 253-279 (2012)
4. Braun, H., Weisbrod, J.: Evolving neural feedforward networks. In: Artificial Neural Nets and Genetic Algorithms. pp. 25–32. Springer (1993)
5. Floreano, D., Dürr, P., Mattiussi, C.: Neuroevolution: from architectures to learning. Evolutionary Intelligence 1(1), 47–62 (jan 2008)
6. Fogel, D.B., Fogel, L.J., Porto, V.: Evolving neural networks. Biological cybernetics 63(6), 487–493 (1990)
7. Goodfellow, I., Bengio, Y., Courville, A.: Deep Learning. MIT Press (2016)
8. Gruau, F., Whitley, D.: Adding learning to the cellular development of neural networks: Evolution and the baldwin effect. Evolutionary computation 1(3), 213–233 (1993)

9. Ha, D.: A visual guide to evolution strategies. blog.otoro.net (2017), http://blog.otoro.net/2017/10/29/visual-evolution-strategies/
10. Hansen, N.: The cma evolution strategy: A tutorial (Apr 2016)
11. Hasan, B.H.F., Saleh, M.S.M.: Evaluating the effectiveness of mutation operators on the behavior of genetic algorithms applied to non-deterministic polynomial problems. Informatica 35(4) (2011)
12. Hausknecht, M., Lehman, J., Miikkulainen, R., Stone, P.: A neuroevolution approach to general atari game playing. IEEE Transactions on Computational Intelligence and AI in Games 6(4), 355–366 (2014)
13. Mirjalili, S.: Evolutionary Algorithms and Neural Networks. Springer International Publishing (2018)
14. Mnih, V., Badia, A.P., Mirza, M., Graves, A., Lillicrap, T., Harley, T., Silver, D., Kavukcuoglu, K.: Asynchronous methods for deep reinforcement learning. In: International conference on machine learning. pp. 1928–1937 (2016)
15. Mnih, V., Kavukcuoglu, K., Silver, D., Graves, A., Antonoglou, I., Wierstra, D., Riedmiller, M.: Playing atari with deep reinforcement learning. arXiv preprint arXiv:1312.5602 (2013)
16. Mnih, V., Kavukcuoglu, K., Silver, D., Rusu, A.A., Veness, J., Bellemare, M.G., Graves, A., Riedmiller, M., Fidjeland, A.K., Ostrovski, G., et al.: Human-level control through deep reinforcement learning. Nature 518(7540), 529 (2015)
17. Montfort, N.: Racing the beam: The atari video computer system (2011)
18. Olive, D.J., Olive, D.J., Chernyk: Robust multivariate analysis. Springer (2017)
19. Rumelhart, D.E., Hinton, G.E., Williams, R.J.: Learning internal representations by error propagation. Tech. rep., California Univ San Diego La Jolla Inst for Cognitive Science (1985)
20. Salimans, T., Ho, J., Chen, X., Sidor, S., Sutskever, I.: Evolution strategies as a scalable alternative to reinforcement learning. arXiv preprint arXiv:1703.03864 (2017)
21. Schulman, J., Wolski, F., Dhariwal, P., Radford, A., Klimov, O.: Proximal policy optimization algorithms. arXiv preprint arXiv:1707.06347 (2017)
22. Stanley, K.O.: Compositional pattern producing networks: A novel abstraction of development. Genetic programming and evolvable machines 8(2), 131–162 (2007)
23. Stanley, K.O., Bryant, B.D., Miikkulainen, R.: Evolving neural network agents in the nero video game. Proceedings of the IEEE pp. 182–189 (2005)
24. Stanley, K.O., D'Ambrosio, D.B., Gauci, J.: A hypercube-based encoding for evolving large-scale neural networks. Artificial life 15(2), 185–212 (2009)
25. Stanley, K.O., Miikkulainen, R.: Evolving neural networks through augmenting topologies. Evolutionary computation 10(2), 99–127 (2002)
26. Such, F.P., Madhavan, V., Conti, E., Lehman, J., Stanley, K.O., Clune, J.: Deep neuroevolution: Genetic algorithms are a competitive alternative for training deep neural networks for reinforcement learning (Dec 2017)
27. Syswerda, G.: Uniform crossover in genetic algorithms. In: Proceedings of the 3rd International Conference on Genetic Algorithms. pp. 2–9. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA (1989)

Hot topics in Human-Computer-Interaction

Carolin Ligensa

Chair for Pervasive Computing Systems

Abstract. This paper identifies emerging topics in the field of Human Computer Interaction (HCI) of significant and growing importance. It identifies those focus points to be health, new research methods in HCI and novel ways of interacting with computers. For health research, there was a clear tendency on finding ways to integrate commonly used technologies into daily health struggles as well as defining the role of social media. In the area of finding new research methods in HCI, improvement was sought for studies through collecting, evaluating and translating data. The field titled as novel ways of interacting with computers deals not only with the design of such novel ways and the evaluation thereof, but also all kind of new possibilities appearing through those ways. It focuses on eye-tracking, epidermal devices and virtual reality.
Different types of papers are distinguished and various research techniques identified and analyzed.

Keywords: HCI, Hot Topics, Health, Medicine, Mental Illness, Assistive Technologies, Fitness, Research, Computer-Interaction, Eye-Tracking, Epidermal devices, Virtual Reality

1 Introduction

This work aims to identify hot-topics of today's Human Computer Interaction (HCI) research. The main focus of HCI research is the improvement of user interaction with any kind of technology. Nowadays technology is integrated into daily activity in every area of our lives. This makes HCI a field that could not be more versatile.

To identify the focus of today's research, I looked at the list of the best papers and honorable mentions of CHI 2019 [1]. CHI is the leading international conference on Human Computer Interaction taking place once a year, held by ACM, the Association for Computing Machinery. With its international relevance, it was the natural choice to investigate HCI research.

This paper summarizes 26 papers in the areas that were identified as hot topics as an attempt on giving the reader an overview over the topics most relevant in today's research. It draws connections between the different topics, identifying prominent and overarching focal points. It also distinguishes different types of papers and identifies and analyzes various research techniques.

2 Emerging Topics in HCI

2.1 Overview

Figure 1 gives an overview over the many topics represented on the CHI 2019 best paper and honorable mentions list [1]. This word cloud was created based on reading the abstracts of all 150 papers and in this way making deductions to their content.

Fig. 1. Wordcloud compiled of the Best Papers and Honorable Mentions of CHI 2019.

As can be seen in Fig. 1, there was a great variety of topics covered multiple times in current research. This is due to the fact that HCI is a very versatile field. In this paper however not all of these areas can be covered. The main focus is going to be on the three biggest areas that were identified: health, challenges of HCI research and interaction with computers in new ways.

2.2 Health

As can be see in Fig. 1, the biggest part of today's research focuses on health issues. In the following, this topics is divided into the areas of Medicine, Mental

Health, Assistive Technology for Disabilities and Fitness for a better overview of the wide range of topics this field represents.

Medicine

The most well-known area of health management is traditional medicine. Treatment however does not solely take place in clinics or doctor's offices anymore. In the following, two novel ways of diagnosing and dealing with disease are introduced.

Self Management In the year 2020, 157 million people all over the world will be suffering from chronical health conditions [19]. Already today, 50 million people in Europe alone suffer from so called multimorbidity, meaning they suffer from multiple chronical health conditions [9]. With a steadily increasing number of chronically ill people, tools for self-care become increasingly important. Self-care was defined by the World Health organization as "the ability of individuals, families and communities to promote health, prevent disease, maintain health, and to cope with illness and disability with or without the support of a health-care provider" [18]. Tools for self-care are mostly mobile applications that help the patients deal with multiple tasks needed to be carried out every day. Improving on those tools can save a lot of time and effort and thus significantly improve quality of life [9].

While use of such tools has clearly shown health benefits, it has been observed that people affected find it challenging to stick to self-care mechanisms [19]. Raj et al. [19] investigate the role of context in self-management at the example of Diabetes Type-1 patients. Context in this case can be any environment or circumstance, e.g. home/travel, work/school, weekends/working days. They find that these contexts highly influence factors like nutrition, physical activity, mood and, in this special case, insulin. Being aware of those contexts can potentially be used for "providing support at the right time, at the right place, and in the right way" and thus encouraging people, not pressuring them. Data regarding these contexts can easily be taken from the user's smartphones. The challenge here clearly lies in the design of those context-sensitive self-care tools. This includes finding relevant factors as well as solutions on how integrate them best. So-called contextual frames help understanding the same factors in different contexts and thereby can help adjusting and optimizing the support to each individual.

Doyle et al. [9] focus on the special burdens experienced by people with multimorbidity using self-care technology. Additionally, they concentrate on elder people, as the probability for chronic disease grows hand in hand with age. Older people might face additional challenges like a lack of sensory, physical and / or cognitive skills as well as technological affinity when interacting with technology. As a consequence, technology for elder people should be "accessible, easy to use and intuitive, shortening the learning curve for this cohort" [9]. They also found that the daily treatment of multiple illnesses often equals excessive demands on

the patient's side. From keeping track of symptoms and taking a potentially vast amount of medication to managing healthcare visits and doctor's appointments, the list of tasks can be overwhelming and sometimes even contradictive. Prioritizing tasks provides a starting point for the patient and supports decisions when having to choose between contradicting assignments. When designing medicinal care for people with multiple chronic illnesses, it can further be helpful to look at the bigger picture of all their illnesses rather than seeing and treating each one individually. Another benefit can be the co-use of the self-care application by both patient and care-taker, as both possess unique but valuable insight into the patient's condition. The patient has a leading edge on his personal state of health while the care taker can see things from a medicinal perspective.

Online Health Communities Online Health Communities are online forums that allow people with similar diagnosis to connect. They act as a support system and offer advice on illness-related issues [27, 28].

As people seek medical advice to personal health problems, they have to reveal a much greater amount of personal data than e.g. when seeking for help in a tech forum. So-called self-disclosure, "the process by which one person verbally reveals information about himself or herself to another" [27], is important for others to understand the exact terms of the problem and give advice accordingly. This of course makes the author vulnerable. Looking at the big picture of social media, people have shown to be more likely to disclose personal information that might reflect in them negatively in private channels, meaning to a specified audience, rather than in public for everyone to see. Anonymity brings safety. Online Health Communities provide both private and public channels, yet they get used differently: Primarily used are public channels for all matters of support; private channels are merely used for follow-ups. Being a community for a specified group of people already gives a more private feel to the public channels. [27]

Another interesting observation made by Young et al. [26] is the differentiation and the distribution of different social roles amongst members of Online Health Communities. While some people might be focused on sharing illness-related information, others might want to share their personal story or give advice to others. What role a member will fill is mostly depended on their goal, their desire to interact with other members and their expectations from joining the community. Over the course of their in the community, every member will obtain different roles, yet stay equally distributed in the community as a whole.

Young et al. [28] have observed these behaviors and patterns to slightly shift when looking at Online Health Communities for illnesses with unknown cause. At the example of a Facebook support group for Vulvodynia, they found that members primarily used the platform "to collectively make sense of their condition". There was also a significantly larger amount of entries concerning how to self-manage daily life with the illness. Additionally, they discovered potential added benefit of self-tracking devices for diseases with unknown cause. Provided with the resulting

pool of first-hand patient data, it might be possible to collectively find a reason for the illness.

Mental Illness

Similar to the online communities discussed in the previous sections, Andalibi's paper [5] focusses on what existing social media networks can do. Sharing mental health issues on identified social networks can be intimidating, since unfortunately, there is still a stigma attached to mental illnesses [5, 11]. Yet it has proven to offer the possibility to form deeper bonds with similar-conditioned people than looking for support on an anonymous website. Victims of mental illnesses sharing them online have shown to turn into role-models for others and thereby experienced health improvement themselves. This mentorship-relationship is however complicated by social media platforms, as they "lack affordances that enable the community, particularly new or occasional users, to effectively find discussions as they become buried below new content" [28]. A new function of labelling oneself as a specific group could help finding people with a shared diagnosis. Integrating an online health community into everyday social media instead of marginalizing them also might benefit the demise of mental health stigmata [5].

This is particularly important as more and more people are affected by this. Studies have shown that especially students are increasingly affected by mental health problems. It is even said that mental health is "the hidden price of education". Not only leading to suicide and a lower life-quality, but a decrease in academic performance too, it is naturally recognized as a problem by Universities and researchers. As a result, digital phenotyping was introduced. Digital Phenotyping is a "health surveillance technology" that monitors digital activity. It is proven to detect signs for stress, mood and even signs for depression and suicidal thoughts. It can be applied to monitor all students to identify those affected by mental problems or just specific people that are known to have those issues. It can also be used to monitor students as a whole to give an overview of the general mental condition on Campus as an additional resource to the many studies that have been conducted on this topic. While this technique might help in identifying students with mental health issues that do not seek for help, it remains unclear what is then supposed to help them. Services of counselling and support are already hopelessly overrun by students with the same problems who do to seek help. The collected data could however be of value when designing methods to help victims of mental health diseases. The HCI challenge here lies in bringing the technology to the people, since most feel uncomfortable being monitored in their daily digital activities. In a study executed by Rooksby et al., participants were most concerned about the violation of privacy. These concerns however often came from not fully understanding what was being recorded. Therefore, a user-friendly design of this approach is crucial. [21]

Smartphones take quite powerful roles in our everyday life. It seems only natural to include them in the design of new ways to ensure mental health. Doherty at al.

[8] explore the possibilities of the mental health screening of antenatal woman through self-reporting. An alarming 50 percent of pregnant women suffering from prenatal depression remain undiagnosed. While there are examinations of this illness, those are primarily performed face to face. Women have reported to feel uncomfortable in those situations, unsure of expectations and afraid of stigmata. The leading cause for maternal mortality in the UK is suicide, and not only the mothers are at risk, but the children too. In the study run by Doherty at al., pregnant women were provided with an app on their mobile devices where they could self-report on their mood. This data was then stored encrypted and only when showing risk to a participant's health shared with a doctor to instantly make help available to the patient. Of the women that were diagnosed with prenatal depression through this app, two-thirds weren't detected by conventional methods.

Mental Illness being an increasing field of interest was already recognized by Sanches et al. [22]. They too found the biggest focus of research in this field to be on self-tracking technology and automated diagnosis. In their paper, they evaluate existing research on affective disorders such as depression, bipolarism and anxiety and suggest improvements to today's research. They recognize the main goal of HCI research in this area to be the "positioning Information and Communication Technologies [...] as an important component of therapies, prevention strategies or self-management for people dealing with affective disorders, as well as their peers, caregivers or clinical staff" [22]. Most fitting for this would be full-cycle studies: gathering information, translating that data into design and after that evaluating, e.g. through clinical trials, and thus getting feedback on their effectiveness. Yet they observed a tendency to overreach on data collection and underplay on translating that data into novel technologies. Another point was the collaboration of both technology and therapy. One informing the other, they can improve best when working closely together. Involvement of in-clinic patients in technology design was also found to be beneficial, as they have valuable input to contribute. Considering that research subjects in this case are people suffering from affective disorders, there is a need for encouraging taking precautions to not affect those people, often more unstable and vulnerable, in a negative way. Lastly, they found that novel technologies were in no way utilized on the scale they could be. As seen in one case of virtual reality exposure therapy, this could potentially hold great possibilities and improvements.

Assistive Technologies for Disabilities

Assistive Technologies for People with Visual Impairments With technologies like Alexa and Siri HomePod, Voice User Interfaces increasingly become more present. Not only are they capable of making daily life at home more comfortable, they could also be highly beneficial in other environments. One example is supporting people with visual impairments, as for them, speech seems to be the simplest and most intuitive way of interacting with technology.

Metatla et al. [15] explore this at the defined example of visually impaired students in mainstream schools. It was found that while more and more students with visual impairments are send to mainstream schools and educated together with sighted students, there still seems to be a social barrier between the both groups. Visually impaired students have a harder time participating in class and are often socially isolated. One explanation for this might be that assistive learning techniques are usually designed for single person use and therefore, complicate interactive study techniques like group work projects used in class. The elimination of this example could be easily achieved by a technology aware of its surroundings and context: during group work, the technology would be used on a speaker, enabling interactions all students, visually impaired and sighted. Switching from group work to individual studies could then be easily achieved by plugging in headphones. Another observation made was that visually impaired students in mainstream schools preferred to use assistive technology on their tablets or smartphones. Technology that was developed especially for this purpose, e. g. ear pieces, were perceived as socially awkward, embarrassing and isolating the user in a "technology-bubble".

There are however challenges visually impaired people have to face when interacting with smartphones. Not only touch input can often be more troubling, as visually impaired people tend to only have one hand available with the other hand holding on to a cane, a guide-dog or an accompanying person. Speech output in public raises a number of issues as well, starting with the compromising of output through environmental noise. Privacy concerns have to be considered. Again, there was unease about social salience and awkwardness. These struggles were motivation to Wang et al. [25] for designing their new technology EarTouch. In their approach, interaction with the phone takes place thorough tap and draw gestures of the ear. Holding the smartphone against the ear is a common position, e.g. when taking a phone call or listening to an audio message. It enables confidential speech output and does not stand out in any ostracizing way. Especially challenging was not only the natural condition of the ear, which made it harder to track gestures. The ergonomics too were reversed to what is known from finger interaction, as not the ear, but the device is moved. Ultimately, a user study found their design to be a success, describing it as "easy, fast and fun to use".

Another troubling matter for visually impaired people is the input of text using a smartphone keyboard. When editing text on a smartphone keyboard, most sighted people rely heavily on auto-correcting techniques. These algorithms however cannot simply be copied to screen-reader keyboards for visually impaired people, as their typing mechanisms are significantly different. They enter text letter by letter, not progressing to the next one until the current one is validated. Those factors slow down text input enormously. This lead Shi et al. [23] to develop "VIPBoard", a smart screen-reader keyboard with an adapted auto-correction algorithm. During text input, their algorithm calculates the probability for each letter to come next, considering preceding text as well as touch input

position. The letter with the overall highest probability is then read. Additionally, keyboard-layout and scale of specific keys are adapted whenever the user's touch input does not equal the desired letter. A user study showed a decreased touch error rate of 63 percent and a speed increasement of roughly 13 percent.

Assistive Technologies for Socializing and Personality-Development Socializing and interacting with other people is essential to happiness and health. Especially for a child's development, it is essential they play with their peers. Playing helps you develop social skills as well as self-esteem and a personality. Children with disabilities however often have trouble interacting with other children, as they might be perceived as strange or different. If they have a disability like autism, it might also be uncomfortable for them interacting with others directly. For these children, online communities and social media can act as more comfortable way of socializing. Ringland [20] examines the online community Autcraft, a Minecraft online server adapted especially for autistic children. It is mounted with special plug-ins that prevent any form of bullying like the destruction of someone else's buildings. Surrounded by children with similar conditions, it creates a safe environment. It allows the children to make friends, feel safe and confident about themselves and just play.

Another marginalized group that easily gets excluded from socializing processes are people with dementia in care homes. Especially when the illness is more advanced, they are often labeled as incapable of meaningful social interaction and left by themselves. Foley et al. [12] developed a technology called Printer Pals to encourage social interaction in such care homes. It is a small, receipt-based printer providing the user with short riddles and questions while playing music. Its main purpose is to spark interaction between multiple users. In a user study, elders with dementia seemed very interested in and fond of the novel technology and found it easy to use.

Creativity is one more aspect of self-development and mental well-being. Being creative allows people to relax and be at ease with themselves. This too is sometimes complicated by disorders. Neate et al. [16] introduce "MakeWrite", a prototype app that helps people affected by Aphasia with the process of creative writing. Aphasia is an illness that complicates the process of comprehending and formulating language. The app provides you with a pre-written short story, that is than reduced on the number of words. This can happen both randomly or user-chosen. When less 10 percent of the original text is left, the user can rearrange the words in an order of their liking and randomly create new words to fill gaps. MakeWrite can essentially be used not only for people with Aphasia but everyone experiencing difficulties with creativity, in this case creative writing.

Fitness

Exercise plays a crucial role in physical as well as mental health. Yet more than 1/4 of the world population does not exercise regularly Aladwan et al. [3]

recognize mobile fitness apps as the way to popularize exercising. With most people nowadays having a smartphone and access to internet, mobile fitness apps are a good way to make exercise more approachable.

2.3 Challenges in HCI Research

One thing that naturally seems to come to mind when researching and improving in the field of HCI is improving the research techniques themselves.

As taking surveys and interviews is the gold standard for research in HCI, understanding the participants right is essential for quality outcome. Surveys with young children hold specific challenges. Nowadays, children naturally are a part of the technological world. They have valuable insight into modern technology that is crucial for creating new technologies and evaluating existing ones. Being pre-literate, research methods need to include information transfer by direct speech. This however often leads to flawed results: Not only do they have a harder time answering interview questions in the desired way. It has also shown that adults, even if they might be parents or teachers, perform poorly on understanding and collecting such data. This paper introduces Anchored Audio Sampling, a new way of collecting survey data. It is a program that can be embedded into any android software. Using a microphone, it records participants during their interaction with a technological device during so called anchor moments. These are researcher-chosen pre-selected moments of interest, e.g. the press of a button. It then presents these audio snippets together with the pre- and succeeding audio sequence to provide context. This provides researchers with a less cluttered, valuable data set [14].

Another aspect is of course the design of such experiments in the first place. When coming up with an experiment, researchers often find themselves between saving costs and resources and wanting a high-end quality product. Finding a trade-off between the two while also taking external influences into account is a difficult task. Touchstone2 is a tool designed to help with that. It visualizes correlations between single parameters and also offers interaction with them, thus enabling the user to compare alternate experiment design approaches. It is able to predict statistical significance and estimate the number of research subjects needed to achieve a certain value [10].

Once the data has been collected, it of course needs to be evaluated to find utilization, e.g. in founding design solutions. This is the field of Translational Science: developing scientific knowledge into practice. The major issue in this field is the loss of knowledge during the translation. To decrease this loss and improve translation quality, it is important to understand what obstacles hinder knowledge from progressing from one state to another. The research-practice gap metaphor describes the phenomenon of the two worlds of research and practice seemingly being completely separated. There might even be obstacles like terminology standing in the way of a smooth translation. In contrast to that stands a bidirectional development as a new approach. It proposes the close cooperation of the research and design communities when translating knowledge [7].

2.4 Interaction with Computers in New Ways

Eye-Tracking
Eye-tracking increasingly becomes field of interest as a natural way of interacting with technology. It may in fact soon be built into most of our every-day devices [24]. This offers great opportunities for novel technologies and designs in multiple fields of HCI.

Sindhwani et al. [24] explore the possibilities of eye-tracking in text editing with the development of their program "ReType". They discovered that when editing text at a computer, having a hand leave the keyboard for mouse interaction to relocate the cursor takes up a considerable amount of time and interrupts writing flow. ReType is a text-editing program that uses eye gaze tracking to enable navigation through the text, e.g. to correct a spelling mistake. While it seems only natural to use eye gaze for a task like pointing at a specific area, there are a few challenges that need to be taken into consideration. The Midas Touch metaphor describes the problem of distinguishing between intentional eye movement, meant to trigger an action, and natural, unintentional one. It is also quite challenging to pinpoint the gaze to an exact spot as text on a screen is quite small and closely together. In ReType, these issues are managed through a process called patching. When looking at the typo the user wants to correct, not only do they type in the corrected version, but a preceding and subsequent sequence. This provides the program with context that then can be used as context to the eye-movement tracked. This process is also based on how one would naturally talk about editing a text. A user study found ReType to be the same and even above speed as working with a mouse and an overall improved user experience regardless of typing skills.

Berkovsky et al. [6] take a different direction: they explore the use of eye-tracking in the area of psychology, personality detection to be precise. Personality "refers to a set of individual patterns of behaviors, cognitions, and emotions that predict a human's interactions with their environment" [6]. From personality detection can thus be drawn important conclusions to character traits. This holds potential for novel ways of e.g. recruitment and personnel assessment. It also offers potential for improving HCI designs. Investigating one's personality however is a process prone to faults, as it is mostly conducted through psychological questionnaires or face-to-face interviewing. Obstacles like people not fully understanding questions or feeling uncomfortable answering them makes results biased and flaky. A new approach of making personality detection more objective and fail-safe is the exposure of humans to external stimuli and simultaneous capturing of their external response. In this case, the subject is provided with an image and / or video. Their responding eye movement is captured and fed to a machine-learning algorithm that deduces a number of different personality traits. A high accuracy to predicting personality traits was shown by a user study.

Epidermal Devices

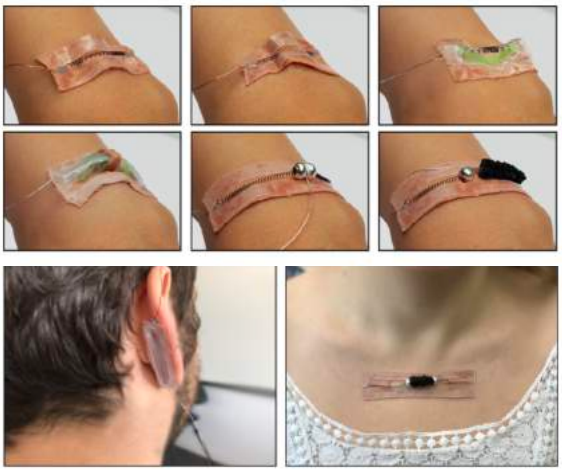


Fig. 2. Example for epidermal devices [13].

As epidermal devices become increasingly popular, Nittala et al. [17] investigate the effect of these skin-worn technologies on the tactile perception. More precisely, they looked at three specific factors: tactile sensitivity, spacial acuity and perceived roughness. As sensoring epidermal techniques, they used PDMS, a material consisting of thin films of poly, and tattoo-paper. While PDMS has 100 times the stiffness of tattoo paper, they both had similar results. They found there to be a connection between the natural sensitivity of the skin and inaccuracy of the technology-covered same spot. The higher the original sensitivity, the more perception will decrease. For example, spacial acuity increased by 50 percent on skin-areas more sensitive and stayed roughly the same everywhere else. On tactile sensitivity and roughness perception, the devices had a much larger effect, with tactile sensitivity threshold increased by 390 percent and the roughness threshold by 490 percent on the most sensitive areas. Overall, they found there to be not a large effect on tactile perception in increasing the stiffness of the device, yet it was found to be better liked by users, as it seemed more sturdy and re-usable.

When it comes to skin-feedback, most is based on vibrational interaction and little attention has been given to more natural options like applying pressure or stretching. Devices developed in this area are often bulky and therefore impractical, disrupting movement and not universally applicable to each body area. Additionally, development so far was always limited to one technique per technology, no one combined several interaction methods on one design. This motivated Hamdan et al. [13] to develop their shape memory alloy spring based

mechanotactile interfaces “Springlets”. Shape memory alloy springs are a type of spring that is especially slim and flexible. Placed in ergonomic stickers, they are movement resistant and can easily be applied to every area of the body like arms or near the head. When a current is applied, they contract similar to human muscle. As can be seen in Fig. 3, there are two different types of actuators. For skin actuators, the interaction takes place at the two ends of the spring where it is attached to the skin. Examples are pinching and directional stretching. End-effector actuators support interactions like pressing, pulling, dragging and expanding by having an additional object added to the spring that is then manipulated by contractions. Even combining two springs or changing the current applied for a different effect is possible. Not only do Springlets offer a wide range of novel ways to interact with skin that are completely silent, they are also easy and cheap to produce and very compact. This could be highly beneficial in many areas like in health and fitness, navigation and Virtual Reality.

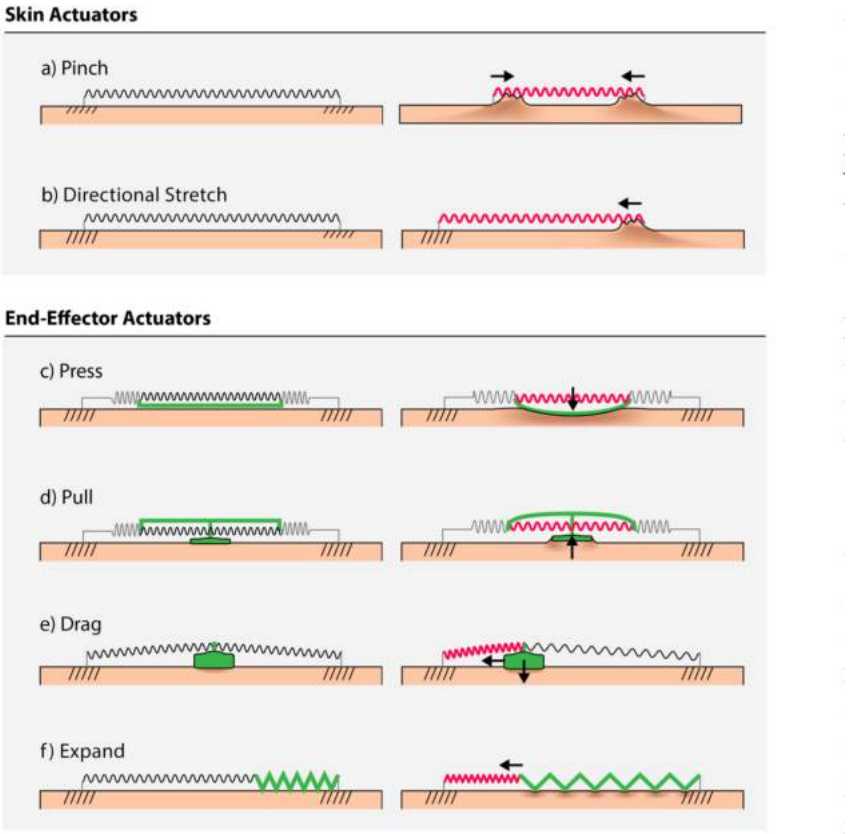


Fig. 3. The two different types of Springlets developed: skin actuators and end-effector actuators [13].

Virtual Reality
The goal of virtual reality technologies is "to replicate the sensation of the physical environment by mimicking people's perceptions and experience of being elsewhere"[4]. With tools like controllers being used for interaction in a virtual environment, a natural design of these too should be a priority. Often interaction with objects is where the illusion of being in a realistic, alternative world breaks [2, 4].

Alzayat et al. [4] developed the Locus-of-Attention Index to provide a measurement on how different tools affect the virtual experience. The Locus-of-Attention Index is based on measuring the so-called embodiment of VR tools. Whether interaction is executed by a body part or external tool can highly influence how the brain processes movement. Embodiment describes the phenomenon of having a tool feel like an extent of your own body. It was measured by Alzayat et al. through a user experiment. They put subjects in a virtual reality setting where they had to complete small tasks and puzzles for a short period of time. Simultaneously, there were color-changing dots projected onto the task board as well as the interaction tool . Participants were instructed to count the changes of color on the task board and the controller separately. The Locus-of-Attention Index was then calculated from a ratio of the dots counted on the task board and the ones counted on the tool. The idea behind this was that the more embodied an interaction tool would be, the less attention users would pay to it. For reference, they conducted the same study with using hands instead of tools, validating this theory.

Fig. 4. Possibilities of haptic interactions in Virtual Reality using a quadcopter [2].

Not only interaction tools are needed to make a virtual experience seem realistic. So-called encountered objects offer a physical surface for the user to directly touch and manipulate. Traditionally used are robot arms. Those are however highly limited in the range they can move in. Even robots that are on

wheels are limited in the height they can reach. Abtahi et al. [2] explore the possibility of a quadrocopter as an alternative, for them having a much wider range and also being more affordable. While there has been work on quadrocopters giving force feedback in virtual reality before, other haptic interactions are possible after overcoming a few obstacles. An example is covering the quadrocopter and its propellers in a mesh cage so it would be safe to touch. The new possibilities were demonstrated by constructing a virtual shopping experience. The quadrocopter was equipped with a piece of cloth and a hanger, enabling users feel clothes and take them from shelves by their hangers (Fig. 4: left and middle). Quadrocopters could also be shut down completely and then lifted by a user, imitating a show box (Fig. 4: right).

3 Best Practices

3.1 Types of Papers

When talking about scientific papers, there are two different types of papers that need to be distinguished.

A paper might be introducing a novel technique. In this case, the authors have developed software like a computer program or an app [10, 16, 23, 25] or even a completely new technology like the small, receipt-based printer "Printer Pals"developed by Foley et al. [12]. They could use the platform of a scientific paper to introduce their **development**, talk about design and conducted user studies.

A paper can also be **analyzing**. The focus here lies on research. It could be conducting interviews or simply summarizing other scientists findings. Conclusions might even be drawn solely based on already existing research. While they might develop prototypes for research purposes, the main difference is that the outcome is not a finished ready-to-use product. Analysis papers solely provide theoretical conclusions like design guidelines.

An aspect worth mentioning is **co-design / co-development**. It is a method of involving directly affected people into the process of developing and designing. E.g. in developing a voice interface for education of visually impaired students in mixed schools, Metatla et al. [15] involved a group of both sighted and visually impaired students.

Figure 5 shows the distribution amongst both all papers from the CHI 2019 Best Paper Award and Honorable Mentions List [1], Fig. 6 shows the distribution amongst those covered in this paper.

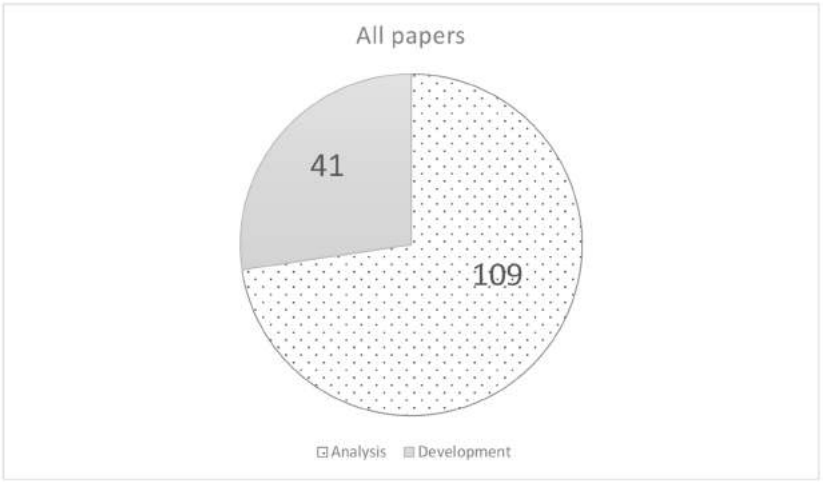


Fig. 5. Categorizing papers into **Analysis** and **Development**. Here: All papers from the CHI 2019 Best Paper Award and Honorable Mentions List [1].

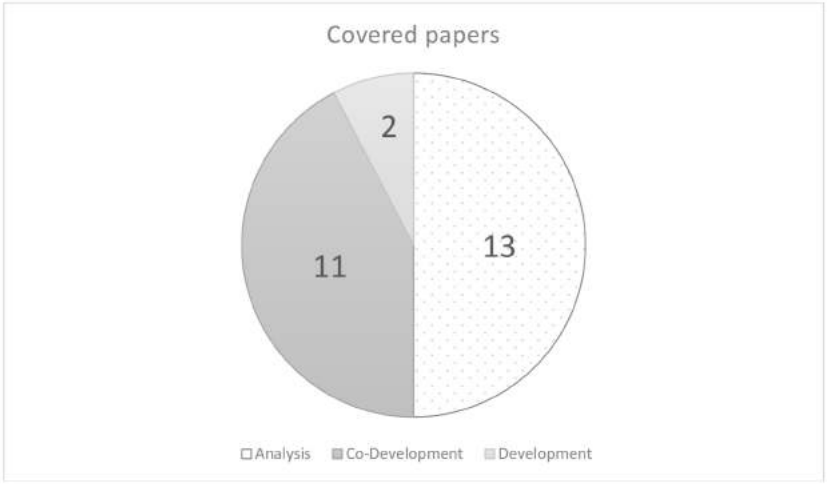


Fig. 6. Categorizing papers into **Analysis**, **Co-Development** and **Development**. Here: Papers covered in this paper.

3.2 Research Techniques

When designing or developing in the field of HCI, data is needed to develop and base theories on. This data can come from reading other scientific papers concerning the same or a similar topic. This however does not always cover it. When researching in a fairly new and unattended field or wanting assessment on a technology you developed, new data needs to be aquired directly from the source. HCI offers a range of pre-defined methods for this purpose:

Observation describes the process of compiling data without direct interaction with people. It can be drawn from user online reviews [3] or through observing the behavioral patterns in an online community [26–28].

User Studies are a popular method in HCI, when searching for feedback on newly developed technologies. The basic principle is setting volunteers up with the technology and drawing conclusions from their interaction. This interaction can be free-use or instructed, giving the participants actions to perform and tasks to complete. It might be set for a time span of about hour in a laboratory [6], but could also be the use and evaluation of a mobile application over several months [8, 14, 19]. The number of participants can range from as little as four to 245. Often mentioned is the study of an entire online community, and even though this is hard to pinpoint to a specific number, it can be estimated even higher than 245. User Studies are often followed by interviewing the participants to get a deeper understanding of their experiences during the study. In fact about fifty percent of the user studies conducted by researches covered in this paper were followed by interviews.

In **interviews**, participants get asked specific questions of interest to the researchers. This might be directed at a specific group of people, e.g. about an online community they're a member of [20, 26–28] or an illness they're dealing with [15]. It could also be a follow-up after a user study [9, 25]. A typical interview lasts between thirty minutes [10] up to 90 minutes [5]. The number of participants is highly similar to the number used in user studies.

Data can also be gathered through giving a **workshop**. A group of ten to thirty people, potentially specifically educated in this field, meets up for what can be a day or a week and together collects their thoughts and experiences on the area.

As for an overview of which studies were used in the papers discussed above, Fig. 7 considers the different types and their representation.

For a closer look as to how many participants were typically used, Fig. 8 offers a relation between a range of numbers of participants and how many studies of the covered papers fall into that range.

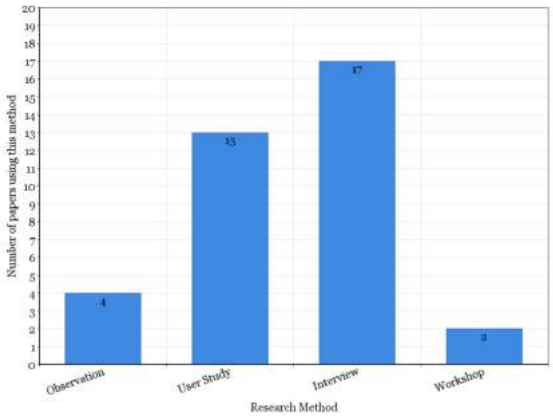


Fig. 7. This diagram shows how often each of the different research methods was used in the pool of papers covered in this paper.

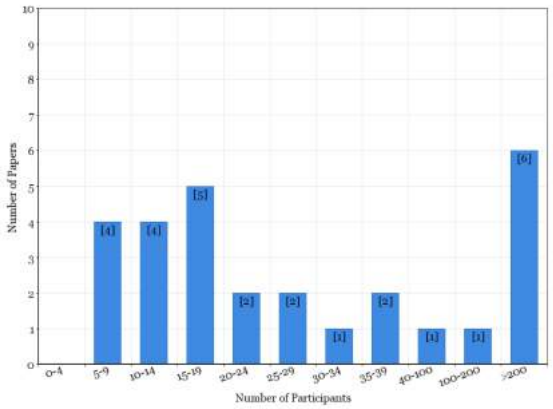


Fig. 8. Diagram showing the number of participants used in covered papers. Bars represent the amount of papers using a number of participants within the span below.

4 Conclusion

Looking at the list of the Best Papers and Honorable Mentions List of the CHI 2019 [1], several hot topics of research were identified. A closer look was taken at the following three: health, challenges in HCI research and novel ways of interacting with computers.
Health being a wide-ranging field, the topic was divided into the areas of Medicine, Mental Health, Assistive Technology for Disabilities and Fitness for a better overview. Overall there was a tendency of finding ways to integrate commonly used technologies into daily health struggles. Smartphones hold new possibilities for self-management of disease [9, 19], while voice user interfaces can highly benefit visually impaired people [15]. Another aspect covered by multiple papers was the role social media can play in illness management, e.g. through supportive online health communities [5, 26–28].
Challenges in HCI research focused on the three aspects of conducting a study. Starting at designing the study in the first place, evaluating qualtiy and costs [10], to handling challenging research subjects [14] up to best utilizing findings [7], the life cycle of a study was covered.
For new ways of interacting with computers, eye-gaze tracking offers new possibilities in all kind of different fields [6, 24], while epidermal device work is still more centered around improving techniques [13] and researching in the way existing ones influences human perception [17]. While both areas are a big part of virtual reality, there is more to it. The greatest problem with the virtual experience at the moment is interaction with tools and objects, for this is often where the illusion of being in a realistic, alternative world breaks [2, 4]. A measurement for the ability of a tool to feel “embodied” as well as new possibilities for interaction objects are discussed.

There were two significantly different types of papers: analyzing and developing papers. While analyzing papers mostly relied on interviews and / or findings of other researches, work shops and especially user studies were highly popular in developing papers. With a variety of techniques used, it is hard to define gold standard. It seems that developing a new technique comes hand in hand with a user study of perception and assessment of this technique. Combining a user study with interviews is a proven concept. There were also notably more development papers than analysis papers in the best paper section of the CHI 2019 best paper section [1], while overall there was a clear lead in analysis papers.

Future work in HCI is likely to continue in a similar direction. As long as there is illness, health is a field that will always remain relevant to humanity. Equally can be said that as long as there is technology, there will be research on new ways to interact with it. Virtual reality is one area that is just on the rise and definitely holds a lot of potential. As to developing new and improved methods of research, improvement might not have the direct visual effect like health or VR, it is however essential for the background of not only those, but every field of research and should therefore always be reinvented and improved.

References

1. Chi 2019 best papers & honourable mentions (2019), https://chi2019.acm.org/2019/03/15/chi-2019-best-papers-honourable-mentions/, last visited on 07.07.2019
2. Abtahi, P., Landry, B., Yang, J.J., Pavone, M., Follmer, S., Landay, J.A.: Beyond the force: Using quadcopters to appropriate objects and the environment for haptics in virtual reality. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 359. ACM (2019)
3. Aladwan, A., Kelly, R.M., Baker, S., Velloso, E.: A tale of two perspectives: A conceptual framework of user expectations and experiences of instructional fitness apps. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 394. ACM (2019)
4. Alzayat, A., Hancock, M., Nacenta, M.A.: Quantitative measurement of tool embodiment for virtual reality input alternatives. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 443. ACM (2019)
5. Andalibi, N.: What happens after disclosing stigmatized experiences on identified social media: Individual, dyadic, and social/network outcomes. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (2019)
6. Berkovsky, S., Taib, R., Koprinska, I., Wang, E., Zeng, Y., Li, J., Kleitman, S.: Detecting personality traits using eye-tracking data. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 221. ACM (2019)
7. Colusso, L., Jones, R., Munson, S.A., Hsieh, G.: A translational science model for hci. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (2019)
8. Doherty, K., Marcano-Belisario, J., Cohn, M., Mastellos, N., Morrison, C., Car, J., Doherty, G.: Engagement with mental health screening on mobile devices: Results from an antenatal feasibility study. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 186. ACM (2019)
9. Doyle, J., Murphy, E., Kuiper, J., Smith, S., Hannigan, C., Jacobs, A., Dinsmore, J.: Managing multimorbidity: Identifying design requirements for a digital self-management tool to support older adults with multiple chronic conditions. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 399. ACM (2019)
10. Eiselmayer, A., Wacharamanotham, C., Beaudouin-Lafon, M., Mackay, W.: Touchstone2: An interactive environment for exploring trade-offs in hci experiment design. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. OSF Preprints (2019)
11. Feuston, J.L., Piper, A.M.: Everyday experiences: Small stories and mental illness on instagram. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 265. ACM (2019)
12. Foley, S., Welsh, D., Pantidi, N., Morrissey, K., Nappey, T., McCarthy, J.: Printer pals: Experience-centered design to support agency for people with dementia. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 404. ACM (2019)
13. Hamdan, N.A.h., Wagner, A., Voelker, S., Steimle, J., Borchers, J.: Springlets: Expressive, flexible and silent on-skin tactile interfaces. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (2019)
14. Hiniker, A., Froehlich, J.E., Zhang, M., Beneteau, E.: Anchored audio sampling: A seamless method for exploring children's thoughts during deployment studies. In:

Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 8. ACM (2019)
15. Metatla, O., Oldfield, A., Ahmed, T., Vafeas, A., Miglani, S.: Voice user interfaces in schools: Co-designing for inclusion with visually-impaired and sighted pupils. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (2019)
16. Neate, T., Roper, A., Wilson, S., Marshall, J.: Empowering expression for users with aphasia through constrained creativity. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 385. ACM (2019)
17. Nittala, A.S., Kruttwig, K., Lee, J., Bennewitz, R., Arzt, E., Steimle, J.: Like a second skin: Understanding how epidermal devices affect human tactile perception. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (2019)
18. Organization, W.H.: Self care for health: a handbook for community health workers & volunteers (2013), http://apps.searo.who.int/PDS_DOCS/B5084.pdf, last visited on 07.07.2019
19. Raj, S., Toporski, K., Garrity, A., Lee, J.M., Newman, M.W.: My blood sugar is higher on the weekends: Finding a role for context and context-awareness in the design of health self-management technology. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 119. ACM (2019)
20. Ringland, K.E.: A place to play: the (dis) abled embodied experience for autistic children in online spaces. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 288. ACM (2019)
21. Rooksby, J., Morrison, A., Murray-Rust, D.: Student perspectives on digital phenotyping: The acceptability of using smartphone data to assess mental health. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 425. ACM (2019)
22. Sanches, P., Janson, A., Karpashevich, P., Nadal, C., Qu, C., Daudén Roquet, C., Umair, M., Windlin, C., Doherty, G., Höök, K., et al.: Hci and affective health: Taking stock of a decade of studies and charting future research directions. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 245. ACM (2019)
23. Shi, W., Yu, C., Fan, S., Wang, F., Wang, T., Yi, X., Bi, X., Shi, Y.: Vipboard: Improving screen-reader keyboard for visually impaired people with character-level auto correction. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 517. ACM (2019)
24. Sindhwani, S., Lutteroth, C., Weber, G.: Retype: Quick text editing with keyboard and gaze. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 203. ACM (2019)
25. Wang, R., Yu, C., Yang, X.D., He, W., Shi, Y.: Eartouch: Facilitating smartphone use for visually impaired people in mobile and public scenarios. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 24. ACM (2019)
26. Yang, D., Kraut, R.E., Smith, T., Mayfield, E., Jurafsky, D.: Seekers, providers, welcomers, and storytellers: Modeling social roles in online health communities. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 344. ACM (2019)
27. Yang, D., Yao, Z., Seering, J., Kraut, R.: The channel matters: Self-disclosure, reciprocity and social support in online cancer support groups. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (2019)

28. Young, A.L., Miller, A.D.: "this girl is on fire": Sensemaking in an online health community for vulvodynia. In: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. p. 129. ACM (2019)

Explainable Deep Neural Networks

Anna Carolina Steyer

TECO, Karlsruhe Institute of Technology

Abstract. Artificial neural networks have a growing importance in our daily life, but still they are like black boxes when it comes to explaining their decisions. This paper introduces eight methods from the literature which analyze the contributions of the input to explain single decisions. The covered approaches are: Sensitivity analysis, Taylor decomposition, Deconvolution, Guided backpropagation, Guided Grad-CAM, Layer-wise relevance propagation, Attention-based models and Explaining black box sequence-to-sequence models. The approaches differ in their applicability to different neural architectures, in how much information they use from the forward pass and whether they can distinguish negative from positive relevance.

Keywords: Explainable artificial intelligence (XAI), Deep neural networks, Deconvolution, Layer-wise relevance propagation, Guided backpropagation, Machine teaching, Verification

1 Introduction

Artificial neural networks have become increasingly ubiquitous. They can enhance our everyday life with music and product recommendations, auto-correction and intelligent smartphone cameras. Although it is annoying if these services do not always work perfectly, it does not have a huge impact on us. An entirely different matter is though if intelligent systems for autonomous driving, medical diagnosis or military operations fail. In those cases, human life is involved and it is thus absolutely crucial to be able to justify the decisions based on such predictions. Neural networks have the drawback that most of them appear to be black boxes in the sense that they aren't transparent concerning their decision making. Therefore, methods for explaining the reasoning of neural networks post hoc are needed. Explaining neural networks is about capturing the model the network has learned after it has been trained. Trying to achieve full model interpretability is not practical since the models learned by deep neural networks are too complex. This paper's focus lies on methods for explaining single decisions by analyzing the contributions of each input feature to the output of interest (*local understanding*). Before going into the details of these local explanation methods in Sect. 3, we will first give a brief introduction to neural networks and the architectures that those methods are designed for in Sect. 2. Section 4 will conclude with comparing these methods and giving an outlook.

2 Brief introduction to neural networks

This section will first introduce the architectural and training fundamentals of neural networks. It will continue with summarizing two common neural architectures: convolutional and recurrent neural networks. At the end of this section, a brief insight into computer vision and natural language processing as major areas of application will be given.

2.1 Basic neural networks

Building blocks The three most elementary building blocks of neural networks are artificial *neurons*, *weighted connections*, and *activation functions*. A neuron holds the real-valued result of an activation function applied to a weighted sum of other neurons' values. The simplest form of a neural network consists only of one neuron (see Fig. 1 left) and thus represents the function

$$y = \sigma(\sum_{i=0}^{n} w_i x_i). \tag{1}$$

with $x_0 = 1$, $x_{i>0}$ the input features, w_i the weights with w_0 called the bias, n the dimension of one input example, σ the activation function and y the output of the neuron.

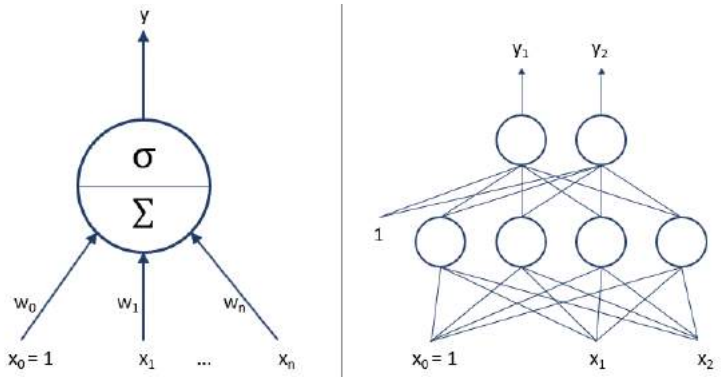


Fig. 1. Feedforward neural network. *Left:* A single neuron that receives input values x_i and computes an output by applying a non-linear activation function σ on their weighted sum. w_0 is called bias. *Right:* A fully connected feedforward multi-layer neural network with one hidden layer.

This single neuron can only represent a tiny piece of information but many neurons joined in a network can model extremely complex functions. When the network is organized in layers of neurons and when these layers are stacked in a way that the output of one layer functions as the input to the following layer,

it is referred to as a *multi-layer* neural network. The layers between the input and output layer are called *hidden*. A famous theorem by Kolmogorov [21] states that every continuous real-valued function can be approximated by a feedforward neural network with a single hidden layer. The non-linear activation function is crucial for this computational power since without it the network would collapse into a single linear model. The most popular activation function nowadays is the *rectified linear unit* function (short ReLU) [24, 32]

$$relu(x) = max(0, x). \tag{2}$$

In Fig. 1 on the right a network with one *fully connected* hidden layer is shown (other layer types will be introduced in Sect. 2.2 and Sect. 2.3). If there are multiple hidden layers, the network is called *deep*. Deep networks are considered to be better than shallow ones because they are able to further abstract from the input with every layer [27]. This *hierarchical learning* [36] is illustrated in Fig. 2 which shows how a network learns to recognize patterns in images starting from basic geometric patterns in the lower layers to more and more specific shapes in the higher layers.

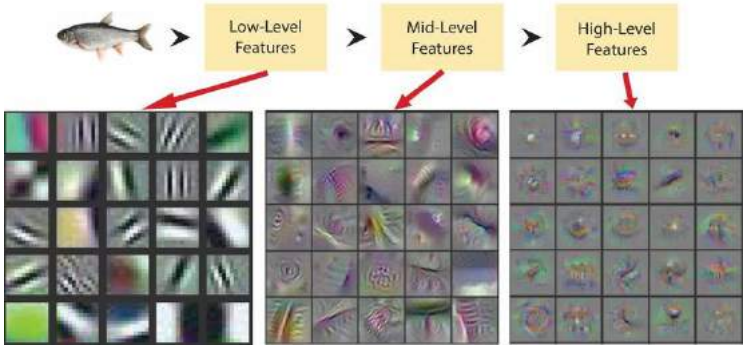


Fig. 2. Hierarchical feature learning for image classification. The lower layers of a network learn to recognize low-level features like edges and color and the following layers will learn more and more complex combinations of these features. (Image source [39])

The number and the dimensions of the hidden layers are *hyperparameters*, which are parameters that have to be chosen by the developer, while the number of neurons in the output layer is determined by the task [14]. A regression task will require as many output neurons as values to be predicted and a neural network designed for classification will need one output neuron per class. Classification additionally requires a layer to transform the activations into class probabilities, for instance, with the *softmax function* [14]

$$softmax(\mathbf{y})_i = \frac{e^{y_i}}{\sum_{j=1}^{C} e^{y_j}} \text{ for } i = 1, ..., C \text{ and } \mathbf{y} = (y_1, ..., y_C) \in \mathbb{R}^C. \tag{3}$$

Training Neural networks are trained with labeled data (*supervised learning*) and end-to-end by repeatedly doing 1. a forward pass for one training example, 2. comparing the output with the known correct result (the *ground truth*) and 3. *backpropagating* the error signal to compute the weight updates accordingly *backward pass* . The objective of the training process is to find the weights that minimize the *loss function* which quantifies how bad the error is with respect to the labeling. The loss function over N training examples for a regression task could be the *mean squared error* [14]

$$\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \tag{4}$$

with $\hat{y}$ the predicted value and y the true label. Since the loss function subject to inputs and weights is very complex, the optimum cannot be computed analytically. Instead, a numerical optimization technique called *gradient descent* (illustrated in Fig. 3) is often used which adjusts each weight w_{ij} in the network towards the negative gradient of the loss L [14]

$$w_{ij} = w_{ij} - \eta\frac{\partial L}{\partial w_{ij}}. \tag{5}$$

The *learning rate* η determines how fast the weights are updated and usually is close to zero to avoid fluctuations. If the learning rate is fixed, the algorithm might more likely miss the optimum or get stuck in a local minimum or plateau. Hence, there are various optimization techniques that define how the learning rate varies in order to improve convergence (e.g. Adadelta [49]). Also, since the loss is not only dependent on the weights but also on the training data, the amount of training data that is used for one weight update has to be chosen [14]. Updating the weights for each single training example is called *stochastic* gradient descent which causes the loss function to fluctuate heavily. Though this helps to find potentially better minima, it also hinders convergence. An alternative technique is the slower *batch* gradient descent which performs only one weight update based on all training examples by taking the average over the whole dataset. *Mini batch* gradient descent is a compromise between those two variants and thus between convergence and exploration. This approach divides the training examples into mini-batches and computes the weight updates based on one mini-batch at a time. This method is computationally efficient, produces stable loss gradients and convergence and if stuck in local minima it is likely to find its way out.

2.2 Convolutional neural networks

Building blocks Since convolutional neural networks (CNNs) [23] are very popular in image processing, the following explanation will focus on two-dimensional input data like images. It has to be remarked though that they can as well be used for one-dimensional data, e.g. in natural language or speech processing [43], and even for three-dimensional data like videos [17]. The most important components

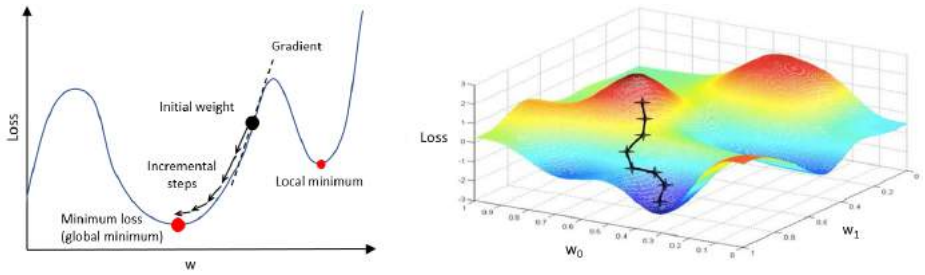


Fig. 3. Gradient descent. The objective is to find the global minimum of the loss function with respect to all weights. Gradient descent, therefore, adjusts the weights step-by-step in the direction of the negative gradient of the loss. *Left:* A loss function with respect to one weight w. *Right:* A loss function with respect to two weights w_0 and w_1 (Adapted from [45]).

of a CNN are the convolutional layers which comprise a stack of so-called *feature maps* which in turn consist of neurons. In contrary to fully connected layers, one neuron always connects to only a subset of neurons from the previous layer (*sparse connectivity*) and shares the number and the weights of these connections with every neuron in the same feature map [14]. The set of weights is called a *filter* (or *kernel*) and its application to the input is called *convolution*. Figure 4 (top) illustrates the convolution operation for one feature map. The filter *slides* over the input and applies its weights at each position. The step size of the movement is given by a hyperparameter called *stride* which, together with the filter and input dimensions and the amount of padding, implicitly defines the dimension of a feature map. While the width and height of the filter are hyperparameters, its depth is determined by the depth of the input (see Fig. 4 (bottom)). For instance, if the inputs are RGB images that have three color channels, then the filters of the first convolutional layer must have a depth of three as well. Further layers will also consist of several channels since this allows the network to represent different features of the same abstraction level in one layer [14]. With every other layer the combination of feature maps enables the network to better generalize from the input data and thus to model more complex features (*spatial hierarchy*). The weight-sharing within each feature map has two advantages. First, it reduces the number of learnable parameters and secondly, the learned features will be *translational invariant* [14]. Since every single feature can be recognized anywhere in the input sequence, in the end, the network will recognize the whole object no matter where.

In CNNs, it is common to include *pooling layers* in between two consecutive convolutional layers. Pooling layers compute one value over a rectangular window (not a cuboid) as they act independently on every feature map. They further don't have any learnable weights and the windows usually don't overlap (the stride equals the kernel size). The advantages are that these layers reduce the number of parameters in higher layers, increase the size of the receptive field and make the representation approximately invariant to small translations of the input

6 Anna Carolina Steyer

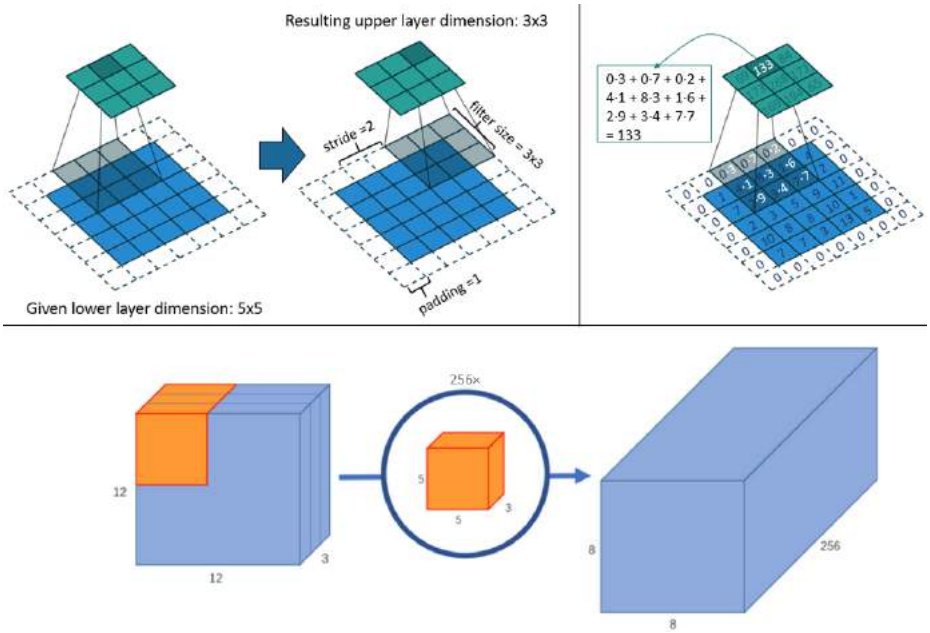


Fig. 4. Convolutional layer. *Top left*: Convolution of a filter of size 3×3 with stride 2 and zero-padding over an input of dimension 5×5 and depth 1 which results in a feature map of dimension 3×3. *Top right*: The value of one neuron in the succeeding layer is computed by applying the filter weights to all previous-layer neurons within the kernel. *Bottom*: The filter extends through the whole depth of 3 of the input. One filter cuboid is defined for each of the 256 output feature maps. (Adapted from [34] and [44])

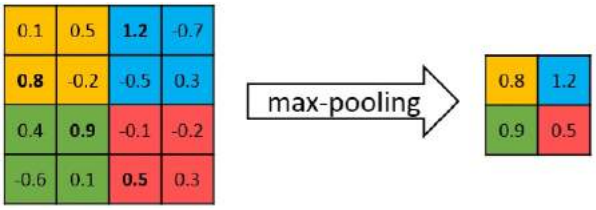


Fig. 5. Max-pooling operation. Only the maximum activation in a window of neurons (here of size 2×2) from the previous layer is kept. (Adapted from [11])

[14]. There a different variants of pooling representing different mathematical operations but the most popular one is *max-pooling* [36] (see Fig. 5). To make the final prediction, the last layer of a network for regression or classification has to be fully connected to combine the features represented by the convolutional layers. An exemplary convolutional neural network with pooling layers is depicted in Fig. 6.

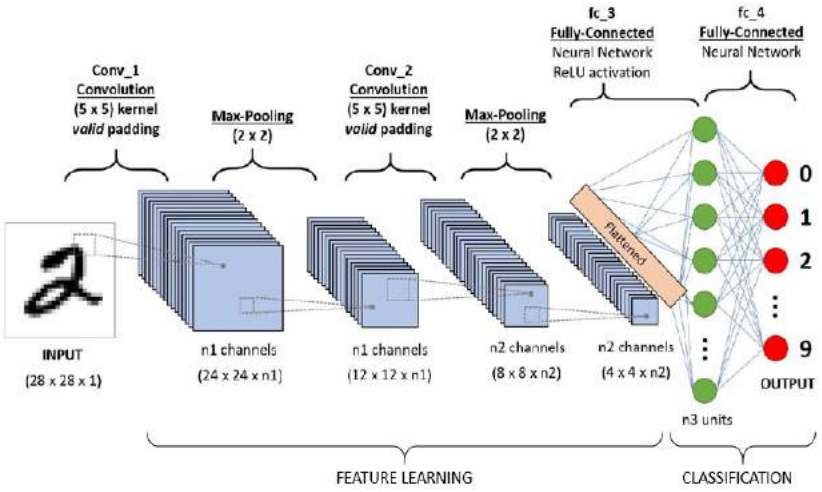


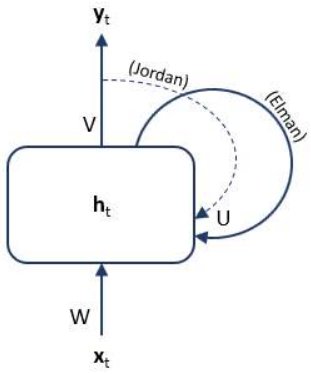
Fig. 6. CNN for classifying handwritten digits. The convolutional layers learn a feature representation while the fully connected layers use these features to make a classification decision. After the last convolutional layer, the feature maps are flattened into a column vector and the softmax function is applied to the last fully connected layer to obtain the class probabilities. The depth of each pooling layer equals the depth of the previous convolutional layer ($n1$ resp. $n2$). Zero-padding is applied to the convolutional layers.

Training The training of CNNs for image-related tasks from scratch requires massive amounts of labeled data which usually can't be obtained for every new task. One option is to use existing datasets available on the internet. The most popular one is provided by the ImageNet database [1] and contains thousands of categories with hundreds of example images. Another option is to apply *transfer learning* [30], i.e. making use of a trained model from a different problem. The extent of reuse can range from only taking the model's weights for weight initialization to copying the lower layers and only training the remaining ones with a task-specific dataset (which now can be smaller because of fewer parameters). This is possible because the first layers of CNNs learn low-level features and thus are likely to be similar for similar tasks. The training of CNNs itself is very similar to networks with fully connected layers, e.g. the loss function for the

classification of images will usually be the same as for classifying any other data and the only difference is how the gradients for the shared weights are calculated.

2.3 Recurrent neural networks

Building blocks *Recurrent neural networks* (RNNs) are specialized for processing sequences of inputs. In contrast to feedforward neural networks, RNNs implement cyclic connections which allow them to maintain a *state*. In theory, this state contains information about all past elements of an input sequence [14]. The structure of a simple recurrent unit is illustrated in Fig. 7. At each time step, the recurrent unit receives the next element from the input sequence and calculates a new hidden state from this input and the previous hidden state [12] or the previous output [18]. The current output in turn is computed from this new hidden state. For longer input sequences, the information from the beginning of the sequence will eventually get lost due to the exponentially smaller weights given to long-term interactions [14]. Thus, these kinds of networks are better suited for tasks without long-term dependencies [8].

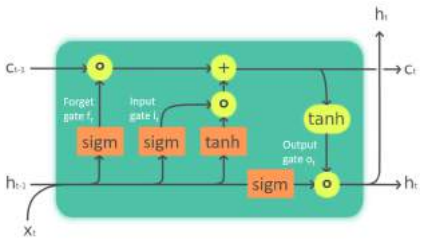


$$h_t = \sigma_h(Wx_t + Uh_{t-1} + b_h) \quad \text{(Elman)}$$
$$h_t = \sigma_h(Wx_t + Uy_{t-1} + b_h) \quad \text{(Jordan)}$$
$$y_t = \sigma_y(Vh_t + b_y)$$

Fig. 7. Simple recurrent unit. At each timestep t, the recurrent unit receives the next element $\mathbf{x}_t$ from the input sequence. It computes the current hidden state $\mathbf{h}_t$ from this input and from either the previous hidden step $\mathbf{h}_{t-1}$ or the last output $\mathbf{y}_{t-1}$. The former version of RNNs is referred to as Elman networks [12] and the latter as Jordan networks [18]. The output $\mathbf{y}_t$ is computed from that current hidden state. The input and output and the hidden state are vectors and hence U, V and W are weight *matrices*.

LSTMs [13, 16] approach this problem by implementing so called multiplicative *gates* that control the information flow. LSTM is the abbreviation of *long short-term memory* which refers to the ability to remember values over abitrarily long time intervals. One unit consists of a *cell state*, which holds the state information, and the input, output and forget gate. A *gate* is a value in $[0, 1]$ which gets multiplied with the value it controls. Intuitively, the input gate controls the amount of new information flowing into the cell, the forget gate regulates how

much information of the cell is kept and the output gate how much of the cell will be used for calculating the activation of the LSTM unit. A schematic overview along with the formulas is provided in Fig. 8.



$$f_t = \text{sig}(W_f x_t + U_f h_{t-1} + b_f)$$
$$i_t = \text{sig}(W_i x_t + U_i h_{t-1} + b_i)$$
$$o_t = \text{sig}(W_o x_t + U_o h_{t-1} + b_o)$$
$$c_t = f_t \circ c_{t-1} + i_t \circ \tanh(W_c x_t + U_c h_{t-1} + b_c)$$
$$h_t = o_t \circ \tanh(c_t)$$

Fig. 8. LSTM recurrent unit. The values of the gates are computed by applying the sigmoid function to the weighted current input x_t and the output of the previous timestep h_{t-1} (W and U are the respective weight matrices and b the bias). The new cell state c_t is then calculated from the old cell state (regulated by the forget gate f_t) and the input x_t together with the old output h_{t-1} regulated by the input gate i_t. The new output is derived from this new cell state modulated by the output gate o_t. The yellow color indicates pointwise operations and the circle $\circ$ refers to pointwise multiplication. (Image adapted from [9] and LSTM formulas from [16])

Training The training of RNNs can be performed with an algorithm called *backpropagation through time*. If the behavior of an RNN is depicted against time (called *unrolling*) for a certain amount of timesteps, it resembles a feedforward neural network (Fig. 9) and thus can be handled with normal backpropagation. The error signal is calculated based on the outputs in the forward pass and propagated backward through the unrolled network. Since the weights of each *copy* of the recurrent neuron are the same, the final update to this weight is the sum of the updates from all timesteps [14].

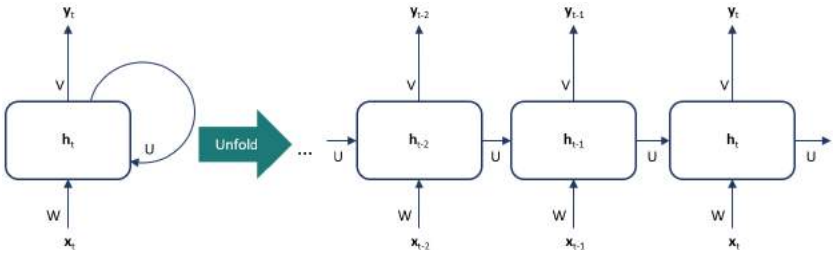


Fig. 9. Unrolled recurrent neural network. The behavior of an Elman recurrent neural network with only one recurrent unit is depicted against time. The weight matrices U, V, and W are shared across time.

2.4 Applications

This paragraph shortly introduces two classical areas of application of neural networks: computer vision and natural language processing. Although the interest in computer vision has been around since the 1960s [31], only with the hardware and the data to train deep CNNs it became so extremely popular. In 2012, a CNN called *AlexNet* [22] achieved a breackthrough in image classification with a top-5 error rate of around 15% in the ImageNet contest (compared to around 25% achieved by the second-best entry). Nowadays, deep CNNs like *ResNet* [15] even slightly outperform humans in object recognition (for which a top-5 error rate of 5.1% has been reported [33]). A choice of tasks going beyond basic object classification is illustrated in Fig. 10. Another interest in computer vision is to extend these concepts also to action recognition in videos (e.g [48]) with the challenges of a huge computational cost, that features have to be observed over a sequence of frames and insufficient training data.

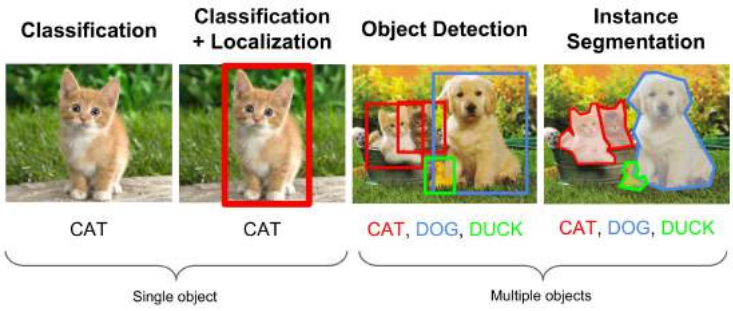


Fig. 10. Object classification and related tasks. For the *localization* of an object, the coordinates of a bounding box around the object of interest are to be predicted. In the case of multiple objects in one image, the neural network has to detect all object instances, possibly of the same class (*detection*). In *instance segmentation*, the single pixels of an object instance have to be determined. (Image source [29])

Natural language processing (NLP) comprises tasks like classification (e.g. sentiment analysis [41]), translation (e.g. machine translation [7]), question answering [20], and text generation (e.g. dialogue systems [38]) where either the input, the output or both are associated with sequences of words. Recurrent neural networks are the most popular choice for these tasks but CNNs have also been successfully used [10]. The combination of computer vision and NLP allows the emergence of new tasks like image captioning [19, 42] or visual question answering [26, 46].

3 Methods for explaining deep neural networks

This section will introduce methods for a better local understanding of neural networks. The methods covered can be divided into functional approaches (Sect. 3.1 Sensitivity analysis and Sect. 3.2 Taylor decomposition), message passing approaches (Sect. 3.3 Deconvolution and Guided backpropagation and Sect. 3.5 Layer-wise relevance propagation) and other (Sect. 3.4 Guided Grad-CAM, Sect. 3.6 Attention mechanism and Sect. 3.7 Explaining black box sequence-to-sequence models). Functional approaches analyze the function represented by the neural network locally while message passing approaches backpropagate a relevance signal through the computational graph of the prediction. In either case, the explanation consists of the resulting relevance scores that indicate to what extent each input feature (e.g. each pixel in an image) contributes to the output of interest. The scores can be used to compute statistics to summarize the network's behavior or be visualized in heatmaps and graphs for intuitive explanations.

3.1 Sensitivity analysis

A neural network can be approached as an unknown function and thus be locally analyzed with respect to single inputs. In a classification task, the output $f_c(\mathbf{x})$ is used for this local analysis (see Fig. 11). The local gradient for instance, shows how *sensitive* the output is to small changes in the input features. A common formulation of this sensitivity measure is [28]

$$S_i(\mathbf{x}) = (\frac{\partial f_c}{\partial x_i})^2 \tag{6}$$

with $f_c(\mathbf{x})$ the output for class c from the layer preceding the softmax layer and S_i called the sensitivity score with respect to one element x_i of the input vector $\mathbf{x}$.

Figure 12 illustrates the drawback of sensitivity analysis. The heatmaps showing the sensitivity scores are spatially discontinuous and scattered which can be explained by the nature of the gradient. A high gradient refers to the input features that would make the input belong more or less to the target class and thus the sensitivity scores are not an explanation of the function value $f_c(\mathbf{x})$ itself but of its local slope [28].

3.2 Taylor decomposition

Another approach is to locally approximate f_c by a first-order Taylor expansion in multiple variables at a root point $\tilde{\mathbf{x}}$ in the neighborhood of $\mathbf{x}$ [6]

$$f_c(\mathbf{x}) \approx f_c(\tilde{\mathbf{x}}) + \sum_{i=1}^{d} \left.\frac{\partial f_c}{\partial x_i}\right|_{\mathbf{x}=\tilde{\mathbf{x}}} \cdot (x_i - \tilde{x}_i). \tag{7}$$

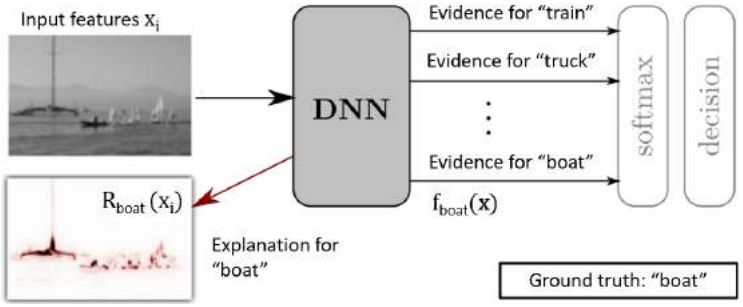


Fig. 11. Explaining a neural network for image classification locally. The output $f_c(\mathbf{x})$ of the last layer, before the softmax function gets applied, indicates to which class c the input $\mathbf{x}$ belongs to. The explanation for the network's decision is a set of relevance scores $R(\mathbf{x})$ indicating the relevance of each input pixel for the decision. (Adapted from [28])

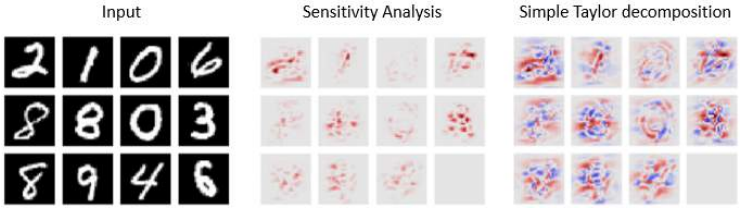


Fig. 12. Sensitivity analysis and simple Taylor decomposition. The inputs are examples of handwritten digits (*left*) and the corresponding scores from sensitivity analysis (*middle*) and simple taylor decomposition (*right*) are visualized in heatmaps. Red color indicates positive scores while blue negative ones. (Adapted from [28])

If $\tilde{\mathbf{x}}$ is chosen to satisfy $f_c(\tilde{\mathbf{x}}) = 0$, then the function value $f_c(\mathbf{x})$ is decomposed into a sum of values for each input feature. Thus, those values can be interpreted as scores and the decomposition as an explanation. The linear approximation is especially applicable for homogenous piecewise linear functions since the higher-order terms, which would get ignored by the first-order Taylor expansion, are zero anyway. For instance, neural networks using the ReLU activation function without biases belong to that class [3]. Moreover, for these functions it is always possible to find a root point in the same linear region as $\mathbf{x}$ that is near the origin. The function from above can then be rewritten as

$$f_c(\mathbf{x}) \approx \sum_{i=1}^{d} \frac{\partial f_c}{\partial x_i}\bigg|_{\mathbf{x}=\tilde{\mathbf{x}}} \cdot x_i. \tag{8}$$

Interestingly, these scores can be interpreted as the product between the sensitivity as introduced above and the saliency given by the input value. An

example of output scores from the simple Taylor decomposition method Eq. (8) is shown in Fig. 12 in a heatmap.

3.3 Deconvolution and guided backpropagation

Both, the deconvolution method of Zeiler and Fergus [50] and the guided backpropagation method by Springenberg et al. [40] revert the computations of CNNs layerwise to tell what pixels of an input image have been relevant for the classification decision. The relevance signal is, starting at the output layer, backpropagated through the computational graph down to the input layer. Again, the initial relevance value is the activation for the class of interest from the layer previous to the softmax layer (Fig. 11). The explanation methods are designed for CNNs with max-pooling layers that use the ReLU activation function. The convolutional layers get inverted by applying the transposed filter matrices to the relevance signal while the unpooling assigns all relevance to the neuron with the maximum activation from the layer below. For the reversion of the ReLU non-linearity, the deconvolution approach keeps all positive relevance and maps all negative to zero which equals applying the ReLU function to the relevance signal. In contrast, guided backpropagation additionally uses the activations from the forward pass to only keep the relevance values that are positive and also correspond to a positive activation. The differences between the two methods for reverting the ReLU non-linearity are illustrated in Fig. 13.

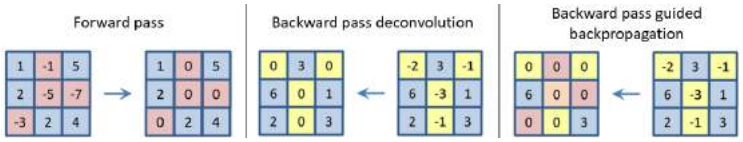


Fig. 13. Reverting the ReLU-nonlinearity. *Left:* Application of the ReLU activation function in the forward pass. *Middle:* The backpropagation of the relevance signal through the ReLU-nonlinearity for the deconvolution method. This equals applying the ReLU function again and thus keeping only the positive relevance. *Right:* Guided backpropagation additionally keeps only the relevance values which are positive and correspond to a positive activation from the forward pass. (Adapted from [40])

By using the activations from the forward pass only in the unpooling layers, the deconvolution method highly depends on the network architecture. If applied to a network without any pooling layers, the heatmaps for one output would thus look the same regardless of the input (see Fig. 14). This is not only problematic for explaining a particular decision but also with more complex input images since there can not exist a single heatmap for visualizing the relevant features of all kinds of images that belong to one class. For this reason, guided backpropagation might be preferred to the deconvolution method, especially for networks without or only a few max-pooling layers. A drawback of both methods is that since

14 Anna Carolina Steyer

the relevance scores aren't normalized during their backpropagation, they don't allow any interpretation of their absolute values. Also, when reverting the ReLU function, negative relevance gets ignored and thus the information about what pixels are contradicting a classification decision is lost.

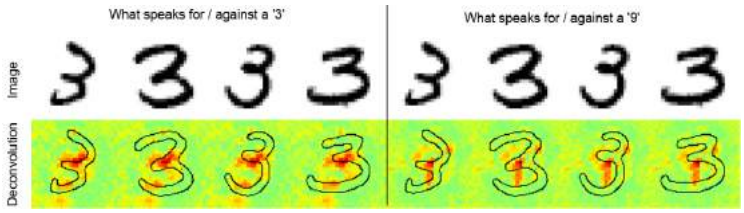


Fig. 14. Deconvolution in a network without max-pooling. In a CNN with only convolutional layers, the deconvolution method for explaining a classification decision will produce the same heatmaps for any inputs. (Adapted from [35])

3.4 Guided Grad-CAM

Guided backpropagation and deconvolution have one major disadvantage for explaining a particular classification decision. The explanations for the same input images will be very similar regardless of the chosen class of interest. This is especially relevant for images that contain objects from different classes. Figure 15 on the left shows the explanations produced by guided backpropagation. From these explanations, it is not apparent whether they are showing the evidence for the cat or the dog. Guided Grad-CAM introduced by Selvaraju et al. [37] approaches this issue by combining a high-resolution pixel-space gradient visualization like guided backpropagation with the Grad-CAM method. The latter uses the gradients of the prediction $f_c(\mathbf{x})$ (Fig. 11) with respect to the activations from the last convolutional layer (before the fully connected layers if there are any). Since every feature map in the last convolutional layer has by definition the same size as the input image, the heatmap pixels can be computed by taking a weighted sum of the activations over the channels. The ReLU function is applied to these results to highlight only the pixels that have a positive influence on the class of interest.

$$R_{ij}^{c} = ReLU\left(\sum_{k} \alpha_k^c a_{ij}^k\right) \tag{9}$$

with a the activations from the last convolutional feature map, $(i,\ j)$ the two-dimensional position in the feature map or heatmap, k the channel, α the

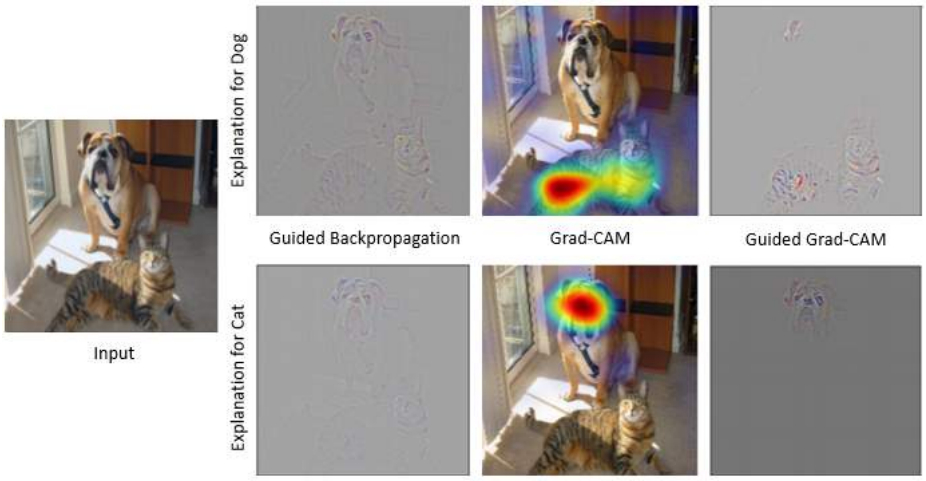


Fig. 15. Guided Grad-CAM. The input image shows a dog and a cat. *Left:* Guided backpropagation produces for both classes similar-looking explanations. *Middle:* The explanations produced by Grad-CAM localize the cat and the dog respectively but don't highlight the supporting fine-grained features like stripes, eyes, and ears. *Right:* Guided Grad-CAM, as a combination of these methods, yields a both localized and fine-grained explanation. (Adapted from [37])

weights for each channel and c the respective class. The weights α_k^c are calculated by taking the average over all gradients in one channel.

$$\alpha_k^c = \frac{1}{i \cdot j} \sum_i \sum_j \frac{\partial f_c(\mathbf{x})}{\partial a_{ij}^k} \tag{10}$$

This results in a very coarse but localized heatmap (see Fig. 15, middle). The combination of Grad-CAM with guided backpropagation by a pointwise multiplication results in guided Grad-CAM which produces a both localized and high-resolution explanation (Fig. 15 (right)). The guided Grad-CAM method is most easily used in image classification tasks but it can be used for any differentiable output. The authors show its application also for image captioning and visual question answering.

3.5 Layer-wise relevance propagation

Another pixel-wise and class-discriminative explanation method is layer-wise relevance propagation (LRP) [6, 28]. Similarly to deconvolution and guided backpropagation, this method backpropagates a relevance signal through the computational graph to compute feature-wise explanations. The difference is that the activations from the forward pass are used for the reversion of all layers. The idea is that the relevance of a neuron in a weighted connection should be

proportional to its contribution to the layer's output in the forward pass. Thus, one rule for calculating the relevance of a neuron j could be

$$R_j = \sum_k \frac{a_j w_{jk} + \frac{b_k}{n}}{\sum_i a_i w_{ik} + b_k} R_k \tag{11}$$

with the activations $a_i = \sigma(\sum_i a_i w_{ik} + b_k)$ for a neuron i, weights w_{ik} from i to another neuron k, b_k the bias and n the total number of the previous layer's neurons to which k is connected. In this way, all neurons of a layer get their share from each neuron of the layer above and thus the total sum of relevances stays the same (*relevance conservation*). For simplicity, the terms containing the bias b_k can be omitted but this makes the rule only *approximately* relevance conserving. To avoid that the denominator becomes zero, a small stabilization term can be added [35]. Equation (11) considers both positive and negative relevance equally. It is also possible to ignore negative relevance to produce a more straightforward explanation by using the following rule which considers only the positive weights (indicated by $()^+$):

$$R_j = \sum_k \frac{a_j w_{jk}^+}{\sum_i a_i w_{ik}^+} R_k. \tag{12}$$

Similarly, positive and negative relevance could also get weighted differently with the rule from above generalized to the $\alpha\beta$-rule given by

$$R_j = \sum_k \left(\alpha \cdot \frac{a_j w_{jk}^+}{\sum_i a_i w_{ik}^+} + \beta \cdot \frac{a_j w_{jk}^-}{\sum_i a_i w_{ik}^-} \right) R_k \tag{13}$$

where $\alpha + \beta = 1$ and $\beta \leq 0$. Figure 16 shows exemplary heatmaps obtained by using different α and β.

Equations (11) to (13) can be applied to any layers with weighted connections such as fully connected or convolutional layers but also to simple recurrent units as in Fig. 7. For the *multiplicative interactions* in the more complex recurrent units such as LSTMs (Fig. 8) though, another rule is needed. Arras et al. [5] suggest to redistribute the whole relevance to the neurons which hold information about the input, i.e. c_t and h_t, and to assign zero relevance to the gates i_t, f_t and o_t. The intuition behind this rule is that the aim is to determine the relevance of each input feature and not of meta information which only controls how much information is kept.

Arras et al. [5] use this rule together with a version of Eq. (11), with stabilisation terms and without considering the bias, for a bi-directional LSTM for sentiment analysis in movie reviews. The results are visualized by highlighted words in the original text that show how much they support the classifier's decision. Since LRP computes scores for every dimension of the word embedding vector, they are added up to obtain only one relevance value per word. Figure 17 shows exemplary sentences and their word relevances with respect to the ground truth. LRP reveals how the network is able to distinguish words that are indicative of a negative review like *horrible* (3), *disaster* (6) or *repetitive* (9)

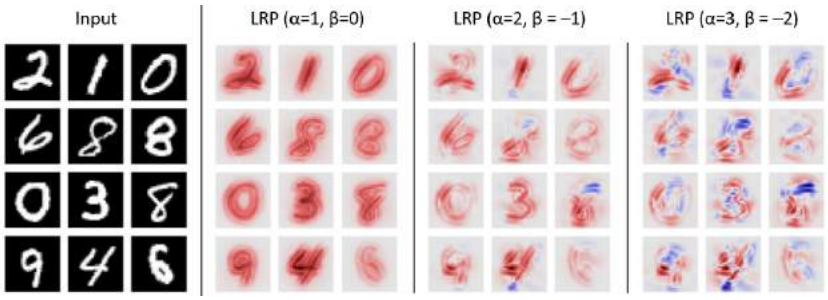


Fig. 16. LRP explanations for different α and β. Explanations for a CNN which has been trained on images of handwritten digits. The heatmaps visualize the relevance intensities subject to the choice of hyperparameters α and β. Allowing for negative relevance by setting $\alpha = 2$ and $\beta = -1$ reveals what pixels contradict the correct classification such as the missing piece in the upper loop of the eight. The share of negative relevance in the third setting with hyperparameters $\alpha = 3$ and $\beta = -2$ makes up about one third of the total relevance which distracts too much from the positive evidence. (Adapted from [28])

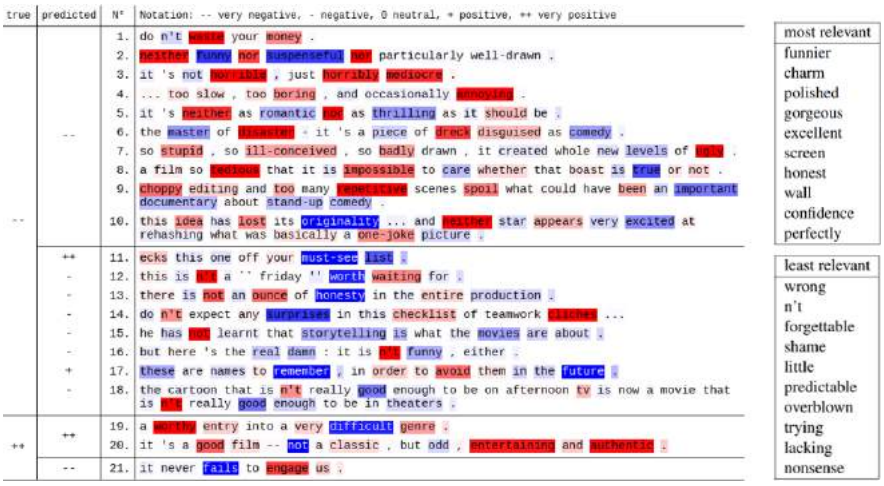


Fig. 17. LRP for explaining sentiment classification. *Left:* Positive relevance for the true target class (left column) is highlighted in red and negative relevance in blue. The color intensity is normalized to the maximum absolute relevance in each sentence. *Right:* For the class *very positive* (++) the ten most and the ten least relevant words from the test dataset are shown. (Adapted from [5])

18 Anna Carolina Steyer

from words that are used to express positive emotions like *funny* (2), *thrilling* (5) or *worthy* (19). The examples 11, 17 and 21 have been wrongly classified and when looking at the explanations produced by LRP it is clear why: *must-see list*, *remember* and *future* are words that are more likely to be used in a positive review while *fails* would rather be used in a negative one. The explanation for sentence 18 indicates that the network has to some extent learned to deal with negations. The positive word *good* is preceded by a *n't* which is highlighted in red (indicating a negative sentiment) while in sentence 1, *n't* is followed by *waste* and highlighted in blue (contradicting a negative sentiment). The authors also compute the relevance scores over the whole test dataset to obtain lists of the most and least relevant words for each class. These lists can give a quick overview of what features are relevant for the network to decide for a particular class. The lists for the *very positive* sentiment-class are shown in Fig. 17 on the right.

In another paper, Arras et al. [4] apply LRP to the task of predicting the topics of newsgroup posts. Figure 18 shows the explanations produced by LRP of the same example for two different categories. They differ meaningfully which indicates that LRP is class-discriminative.

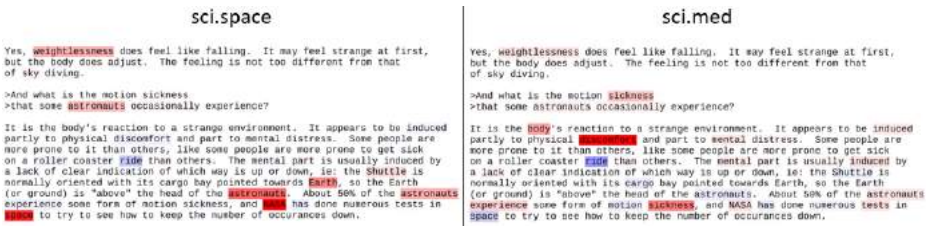


Fig. 18. LRP explanations for the classification of newsgroup posts. LRP reveals the words that are indicative of different categories in the same example. (Adapted from [4])

3.6 Explainability in attention-based models

A concept called *attention mechanism* allows a neural network to focus on a different subset of its input when making different predictions. An example of use for image captioning is shown in Fig. 19. The network has learned to focus on a different part of the image for every word in the resulting caption and thus naturally explains its predictions.

The idea of how attention can improve predictions can be easily understood by looking at an *encoder-decoder* architecture for machine translation (see Fig. 20). The encoder is a recurrent neural network which processes the input sentence and encodes it into a single *context vector*. This context vector is used as the initial hidden state of another recurrent neural network called the decoder [14]. At the beginning, the input to the decoder is a start-of-sentence token and at each

Fig. 19. Attention mechanism in image captioning. The underlined word is produced when looking at the *white blob* in the image. The wrong captions become more intelligible when looking at what part of the image was used for the prediction of a particular word. (Adapted from [47])

following time step, the generated word from the previous step becomes the new input. The output sentence is generated word by word but the information about the input sentence used to predict the words stays the same. Instead of using only the last hidden state of the encoder, the attention mechanism calculates a weighted sum over the intermediate encoder hidden states [25]. The attention weights used for this are different for every decoder time step as they depend on the context of the already generated output [7].

3.7 Explaining black box sequence-to-sequence models

Alvarez-Melis and Jaakkola [2] propose a method for explaining black box sequence-to-sequence models. In contrary to the other methods introduced in Sect. 3.1 to 3.6, this method doesn't rely on having access to *any* internal parameters (*oracle access*). The model of interest doesn't even have to be a neural network, it could also be a human for instance. The proposed method is based on querying the black box with perturbed inputs and results in groups of related input-output tokens.

Figure 21 shows a schematic representation of the pipeline of this explanation method. The first step is the creation of perturbed versions of the input which are semantically similar but slightly differ in the particular elements and their order. The authors propose a variational autoencoder for automatically generating such meaningful perturbations for sentences. The second step is a causal inference model based on a Bayesian approach of logistic regression which results in a set of dependency coefficients between the original input and output elements along with their uncertainty estimates. The final step is the selection of only the relevant input-output dependencies to allow an easier interpretation. The authors treat this selection problem as a graph partitioning problem of a dense bipartite graph for interval estimates of the edge weights. Figure 22 shows how an explanation of this method for a translation from German to English could look like.

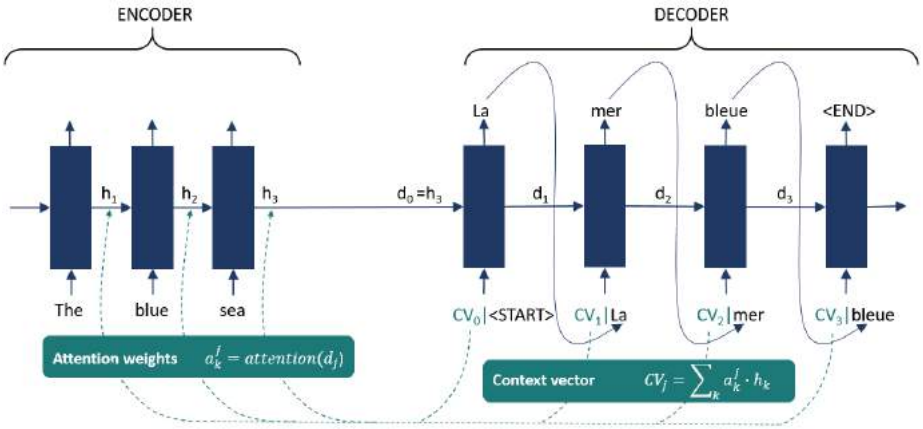


Fig. 20. Attention mechanism in machine translation. The difference to the normal encoder-decoder structure (in blue) is that the inputs to the decoder are a concatenation of the last generated word and a context vector that is produced by the attention mechanism (in green). The context vectors CV_j are calculated as a weighted sum over the intermediate hidden states h_k of the encoder. The attention weights α_k^j depend on the decoder hidden states d_j and thus the context of the previously generated words.

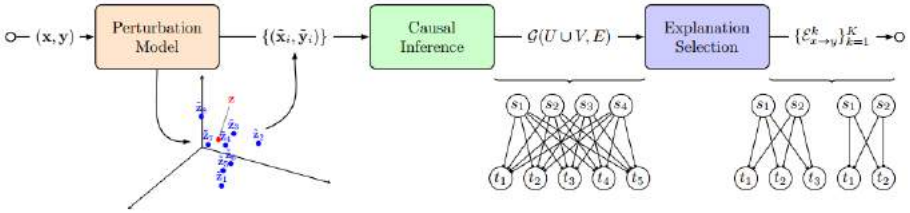


Fig. 21. Explanation method for black box Seq2Seq models. This method doesn't rely on having access to any internal parameters. *Step 1:* A perturbation method is needed to produce semantic similar versions of the input sequences. *Step 2:* To produce an explanation for a particular input sequence, the black box model is queried with the perturbed versions of this input. By analyzing the respective outputs with respect to the presence of input tokens, conclusions about the relations between the input and output tokens can be drawn. *Step 3:* Only the most relevant relations are kept to make the explanation easier interpretable. (Image source [2])

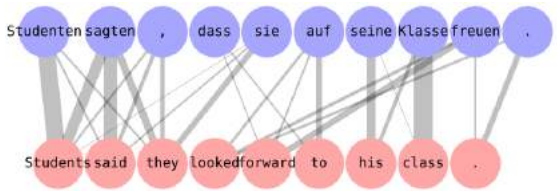


Fig. 22. Explanation of a black box translation. The gray connections show the dependencies between the words and their strength the intensity of the relation. (Image source [2])

4 Conclusion and outlook

This paper presents a review of explanation methods for deep neural networks which compute relevance scores of the input features that indicate the extent of their contribution for creating a prediction. The approaches differ in their applicability to different neural architectures, in how much information they use from the forward pass and whether they can distinguish negative from positive relevance. Table 1 provides a comparison of the methods with respect to these characteristics.

Sensitivity analysis (Sect. 3.1) analyzes the gradients of a prediction with respect to the input. The resulting scores indicate the extent of which the network is sensitive to small changes in the input features. Thus, these scores are rather an explanation of the local slope than of the function value itself. Furthermore, sensitivity analysis does not distinguish between positive and negative effects and due to the local analysis, the resulting heatmaps can be very discontinuous.

Simple Tayor decomposition (Sect. 3.2) requires neural networks to use homogenous piece-wise linear activation functions. If that is the case, the function represented by the model can be approximated with a first-order Taylor series expansion which results in a decomposition into the gradient and the input value. The resulting explanation scores can thus be interpreted as a product between sensitivity and saliency.

The deconvolution method (Sect. 3.3) is able to explain classification decisions of CNNs that use the ReLU activation function and max-pooling. The idea is to revert the computational graph of the network layer-wise to obtain the input features which have been relevant for the output of interest. The reversion of the max-pooling layers is the only time when information from the forward pass is used. Therefore, when applied to a network without pooling, the resulting explanation will rather be a general representation for a class than an explanation for a decision based on a particular input. Guided backpropagation (3.3) is very similar to deconvolution but doesn't rely on the network to have max-pooling layers. This is achieved by not only using the activations from the forward pass for reverting the max-pooling layers but additionally for the ReLU layers.

Guided Grad-CAM builds on guided backpropagation by combining it with a coarse but localized explanation obtained by the Grad-CAM method. Grad-CAM

analyzes the activations of the last convolutional layer to localize the regions that are relevant with respect to a particular classification decision which results in a both class-discriminative and high-resolution explanation.

Layer-wise relevance propagation (3.5) uses the weights of the network together with the activations from the forward pass to distribute a relevance signal in the computational graph. The relevance signal is usually the activation in the last layer that corresponds to the outcome which is to be explained. The distribution preserves the total relevance and allows also for negative relevance which indicates features that contradict a prediction. In theory, LRP can be applied to any networks with monotonous activations and examples of its application to computer vision and NLP classification tasks with CNNs and LSTMs exist.

The attention mechanism (Sect. 3.6) is an example of a neural architecture that naturally provides explanations of its reasoning. In contrary to the other approaches, it aims at explaining the prediction of an output sequence and not of a classification or regression. Attention is usually used for encoder-decoder architectures and its scores indicate which input features have been important for predicting a particular element of an output sequence.

The approach from Sect. 3.7 is also designed for explaining sequence-to-sequence models and excels by not requiring any information from the model or the forward pass like weights or activations. To infer dependencies between the elements of an input and and output sequence, the black box is queried with semantic similar versions of the input. The resulting input-output pairs are analyzed to associate the occurence of tokens in the input and output.

Various factors like the application of neural networks in transport, medicine and military and the current European legislation will foster explainable artificial intelligence in the near future. This paper provided insights into various approaches for designing local explanation methods and such techniques will likely be further developed, especially towards the applicability to a wider range of architectures. In addition to the development of explanation methods, the interest in optimizing future neural networks towards an improved explainability and not only the best accuracy might also grow. Furthermore, techniques like the attention mechanism show the possibility of developing neural networks that can provide an explanation of their reasoning from the start.

References

1. (2016), http://www.image-net.org/
2. Alvarez-Melis, D., Jaakkola, T.S.: A causal framework for explaining the predictions of black-box sequence-to-sequence models. arXiv:1707.01943 (2017)
3. Arora, R., Basu, A., Mianjy, P., Mukherjee, A.: Understanding deep neural networks with rectified linear units. arXiv:1611.01491 (2016)
4. Arras, L., Horn, F., Montavon, G., Müller, K.R., Samek, W.: "What is relevant in a text document?": An interpretable machine learning approach. PloS one 12(8) (2017)
5. Arras, L., Montavon, G., Müller, K.R., Samek, W.: Explaining recurrent neural network predictions in sentiment analysis. arXiv:1706.07206 (2017)

	Network requirements	Relevance signal	Activations used for reverting layers			Negative relevance	Result
			ReLU	Pooling	Weighted connections		
SA	Continuous locally differentiable	$\nabla f_c(x)$	✓ [1]	✓ [3]	✗ [4]	✗	No patterns but single features that make the input belong more/less to a class
Simple Taylor	Homogenous piecewise linear activations	$\nabla f_c(x) \circ x$	Activations always used			✓	• Input patterns relevant for a class • Sum of scores equals $f_c(x)$
Deconv	Feed forward, (max-pooling), ReLU	$f_c(x)$	✗ [2]	✓ [3]	✗ [4]	✗	Patterns relevant for a decision (but not class-discriminative)
Guided Backprop	Feed forward, ReLU	$f_c(x)$	✓ [1,2]	✓ [3]	✗ [4]	✗	
Guided Grad-CAM	Depends on which pixel-wise explanation method is used						Input patterns relevant for a class
LRP	Monotonous activations	$f_c(x)$	–	✓ [3]	✓ [5]	✓	• Input patterns relevant for a class • Sum of scores equals $f_c(x)$
Attention	Architecture using attention	Attention scores	–	–	–	✗	Can only explain one outcome since scores are internal parameters
Black box Seq2Seq	Seq2Seq model	Dependency coefficients	No activations and weights used at all			✗	Can only explain actual (not arbitrary) output sequences

Table 1. Comparison of explanation methods. The methods are compared by means of their requirements, for which layers the activations from the forward pass are needed and whether negative relevance can be computed.
[1] The relevance signal is redistributed only to neurons with positive activations
[2] Only positive relevance signal is redistributed
[3] Activations are used to undo the pooling operation
[4] Relevance signal is redistributed with respect to the weights
[5] Relevance signal is redistributed proportionally to activations and weights

6. Bach, S., Binder, A., Montavon, G., Klauschen, F., Müller, K.R., Samek, W.: On pixel-wise explanations for non-linear classifier decisions by layer-wise relevance propagation. PloS one 10(7) (2015)
7. Bahdanau, D., Cho, K., Bengio, Y.: Neural machine translation by jointly learning to align and translate. arXiv:1409.0473 (2014)
8. Bengio, Y., Simard, P., Frasconi, P., et al.: Learning long-term dependencies with gradient descent is difficult. IEEE transactions on neural networks 5(2), 157–166 (1994)
9. Chevalier, G.: (2018), `https://upload.wikimedia.org/wikipedia/commons/3/3b/The_LSTM_cell.png`
10. Dauphin, Y.N., Fan, A., Auli, M., Grangier, D.: Language modeling with gated convolutional networks. In: Proceedings of the 34th International Conference on Machine Learning-Volume 70. pp. 933–941. JMLR. org (2017)
11. David, E., Netanyahu, N.: Deeppainter: Painter classification using deep convolutional autoencoders. pp. 20–28 (2016)
12. Elman, J.L.: Finding structure in time. Cognitive science 14(2), 179–211 (1990)
13. Gers, F.A., Schmidhuber, J., Cummins, F.: Learning to forget: Continual prediction with LSTM (1999)
14. Goodfellow, I., Bengio, Y., Courville, A.: Deep Learning. MIT Press (2016), `http://www.deeplearningbook.org`
15. He, K., Zhang, X., Ren, S., Sun, J.: Deep residual learning for image recognition. In: Proceedings of the IEEE conference on computer vision and pattern recognition. pp. 770–778 (2016)
16. Hochreiter, S., Schmidhuber, J.: Long short-term memory. Neural computation 9(8), 1735–1780 (1997)

17. Ji, S., Xu, W., Yang, M., Yu, K.: 3D convolutional neural networks for human action recognition. IEEE transactions on pattern analysis and machine intelligence 35(1), 221–231 (2012)
18. Jordan, M.I.: Serial order: A parallel distributed processing approach. In: Advances in psychology, vol. 121, pp. 471–495. Elsevier (1997)
19. Karpathy, A., Fei-Fei, L.: Deep visual-semantic alignments for generating image descriptions. In: Proceedings of the IEEE conference on computer vision and pattern recognition. pp. 3128–3137 (2015)
20. Kembhavi, A., Seo, M., Schwenk, D., Choi, J., Farhadi, A., Hajishirzi, H.: Are you smarter than a sixth grader? Textbook question answering for multimodal machine comprehension. In: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition. pp. 4999–5007 (2017)
21. Kolmogorov, A.N.: On the representation of continuous functions of many variables by superposition of continuous functions of one variable and addition. In: Doklady Akademii Nauk. vol. 114, pp. 953–956. Russian Academy of Sciences (1957)
22. Krizhevsky, A., Sutskever, I., Hinton, G.E.: Imagenet classification with deep convolutional neural networks. In: Advances in neural information processing systems. pp. 109–1105 (2012)
23. Le Cun, Y., Jackel, L.D., Boser, B., Denker, J.S., Graf, H.P., Guyon, I., Henderson, D., Howard, R.E., Hubbard, W.: Handwritten digit recognition: Applications of neural network chips and automatic learning. IEEE Communications Magazine 27(11), 41–46 (1989)
24. LeCun, Y., Bengio, Y., Hinton, G.: Deep learning. Nature 521(7553), 436 (2015)
25. Luong, M.T., Pham, H., Manning, C.D.: Effective approaches to attention-based neural machine translation. arXiv:1508.04025 (2015)
26. Malinowski, M., Rohrbach, M., Fritz, M.: Ask your neurons: A neural-based approach to answering questions about images. In: Proceedings of the IEEE international conference on computer vision. pp. 1–9 (2015)
27. Mhaskar, H., Liao, Q., Poggio, T.: When and why are deep networks better than shallow ones? In: Thirty-First AAAI Conference on Artificial Intelligence (2017)
28. Montavon, G., Samek, W., Müller, K.R.: Methods for interpreting and understanding deep neural networks. Digital Signal Processing 73, 1–15 (2018)
29. Ouaknine, A.: (2018), `https://medium.com/zylapp/review-of-deep-learning-algorithms-for-object-detection-c1f3d437b852`
30. Pan, S.J., Yang, Q.: A survey on transfer learning. IEEE Transactions on knowledge and data engineering 22(10), 1345–1359 (2009)
31. Papert, S.A.: The summer vision project (1966)
32. Ramachandran, P., Zoph, B., Le, Q.V.: Searching for activation functions. arXiv:1710.05941 (2017)
33. Russakovsky, O., Deng, J., Su, H., Krause, J., Satheesh, S., Ma, S., Huang, Z., Karpathy, A., Khosla, A., Bernstein, M.: Imagenet large scale visual recognition challenge. International journal of computer vision 115(3), 211–252 (2015)
34. Saha, S.: (2018), `https://towardsdatascience.com/a-comprehensive-guide-to-convolutional-neural-networks-the-eli5-way-3bd2b1164a53`
35. Samek, W., Binder, A., Montavon, G., Lapuschkin, S., Müller, K.R.: Evaluating the visualization of what a deep neural network has learned. IEEE transactions on neural networks and learning systems 28(11), 2660–2673 (2016)
36. Schmidhuber, J.: Deep learning in neural networks: An overview. Neural networks 61, 85–117 (2015)

37. Selvaraju, R.R., Cogswell, M., Das, A., Vedantam, R., Parikh, D., Batra, D.: Grad-cam: Visual explanations from deep networks via gradient-based localization. In: Proceedings of the IEEE International Conference on Computer Vision. pp. 618–626 (2017)
38. Serban, I.V., Sordoni, A., Bengio, Y., Courville, A., Pineau, J.: Building end-to-end dialogue systems using generative hierarchical neural network models. In: Thirtieth AAAI Conference on Artificial Intelligence (2016)
39. Siddiqui, S.A., Salman, A., Malik, M.I., Shafait, F., Mian, A., Shortis, M.R., Harvey, E.S.: Automatic fish species classification in underwater videos: exploiting pre-trained deep neural network models to compensate for limited labelled data. ICES Journal of Marine Science 75(1), 374–389 (2017)
40. Springenberg, J.T., Dosovitskiy, A., Brox, T., Riedmiller, M.: Striving for simplicity: The all convolutional net. arXiv:1412.6806 (2014)
41. Tang, D., Qin, B., Liu, T.: Document modeling with gated recurrent neural network for sentiment classification. In: Proceedings of the 2015 conference on empirical methods in natural language processing. pp. 1422–1432 (2015)
42. Vinyals, O., Toshev, A., Bengio, S., Erhan, D.: Show and tell: A neural image caption generator. In: Proceedings of the IEEE conference on computer vision and pattern recognition. pp. 3156–3164 (2015)
43. Waibel, A., Hanazawa, T., Hinton, G., Shikano, K., Lang, K.J.: Phoneme recognition using time-delay neural networks. IEEE Transactions on Acoustics, Speech, and Signal Processing 37(3), 328–339 (1989)
44. Wang, C.F.: (2018), https://towardsdatascience.com/a-basic-introduction-to-separable-convolutions-b99ec3102728
45. Wang, R.: (2018), https://thisgirlreina.wordpress.com/2018/07/11/stochastic-gradient-descent-with-restarts/
46. Xu, H., Saenko, K.: Ask, attend and answer: Exploring question-guided spatial attention for visual question answering. In: European Conference on Computer Vision. pp. 451–466. Springer (2016)
47. Xu, K., Ba, J., Kiros, R., Cho, K., Courville, A., Salakhudinov, R., Zemel, R., Bengio, Y.: Show, attend and tell: Neural image caption generation with visual attention. In: International conference on machine learning. pp. 2048–2057 (2015)
48. Yue-Hei Ng, J., Hausknecht, M., Vijayanarasimhan, S., Vinyals, O., Monga, R., Toderici, G.: Beyond short snippets: Deep networks for video classification. In: Proceedings of the IEEE conference on computer vision and pattern recognition. pp. 4694–4702 (2015)
49. Zeiler, M.D.: ADADELTA: an adaptive learning rate method. arXiv:1212.5701 (2012)
50. Zeiler, M.D., Fergus, R.: Visualizing and understanding convolutional networks. In: European conference on computer vision. pp. 818–833. Springer (2014)

Aufmerksamkeitssteuerung durch Haptische Schnittstellen in Beobachtungsaufgaben

Leon Huck*

Karlsruher Institut für Technologie

Zusammenfassung. In dieser Arbeit wird der Einsatzbereich der Aufmerksamkeitssteuerung durch haptische Schnittstellen in Beobachtungstätigkeiten erkundet. Aufmerksamkeitssteuerung wird als eine Ressource definiert, die es zu verwalten gilt. Für Beobachtungsaufgaben werden die Kriterien Relevanz und Erschöpfung als entscheident vorgestellt. Die haptischen Schnittstellen werden nach ihrer Reizübertragung (Elektrische Impulse oder Druck) unterschieden. Dabei lassen sich Charakteristike, wie die Position auf der Haut, die Berührungsfläche und die Dauer, erkennen. Bei den Anwendungen wird zwischen dem jeweiligen Einsatzbereich unterschieden:

- Sinneswiederherstellung: Simulation anderer Sinne über haptische Signale.
- Zwischenmenschliche Kommunikation: Informationsübertragung über haptische Signale, um die Kommunikation zwischen Menschen zu ermöglichen und zu verbessern.
- Leistungssteigerung: Verbesserung von menschlichen Leistungen durch den Einsatz von haptischen Schnittstellen zur Informationsübertragung.
- Erweiterung des Wahrnehmungsspektrums: Verwenden von haptischen Schnittstellen um künstliche Sinne zu erzeugen.
- Zuverlässigkeit Erzeugung: Erweiterung von bereits bestehenden Systemen mit redundanten haptischen Schnittstellen.

* Unter der Betreuung von: Erik Pescara

2

1 Einleitung

Seit der Einführung von Geräten, wie etwa Handies, sind Aufmerksamkeitshinweise durch Vibrationen im Alltag angekommen. So kann das Handy auch in lauten Umgebungen auf neue Mitteilungen aufmerksam machen. Gleichzeitig werden die Mitmenschen nicht durch durchdringende Töne gestört.

Doch bieten haptische Informationen auch außerhalb von einem einfachen Alarmsystem, wie es im besagten Handy zu finden ist, eine Vielzahl an Möglichkeiten zur Informationsübermittlung (vgl. [1]). Diese Möglichkeiten zu untersuchen ist Ziel dieser Arbeit.

Um das Ziel zu erreichen werden Definitionen für Aufmerksamkeitssteuerung und Überwachungsaufgaben eingeführt um anschließend deren Schnittmenge zu betrachten. Dabei werden die Teilbereiche anhand von konkreten Anwendungen erarbeitet und die allgemeinen Erkenntnisse herausgezogen. Dadurch soll der Stand der Wissenschaft festgehalten und potentielle Forschungsfragen aufgedeckt werden.

2 Die Thematischen Teilgebiete

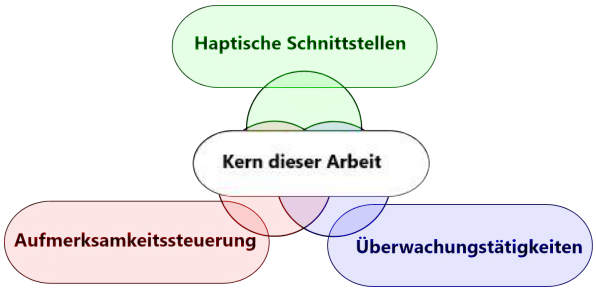


Abb. 1. Graphische Darstellung der Teilgebiete und deren Interaktion anhand eines Venn-Diagramm.

Um eine Diskussion über die möglichen Anwendungen von haptischen Schnittstellen bei der Aufmerksamkeitsbeeinflussung während Beobachtungsaufgaben zu führen ist es unerlässlich die Themenbereiche genau abzugrenzen. Der Grund hierfür ist die Mehrfachverwendung der einzelnen Begriffe. Demzufolge werden die in verwendeten Definitionen vorgestellt.

2.1 Aufmerksamkeitssteuerung

Die menschliche Arbeitskraft ist begrenzt. Das gilt insbesondere für die kognitiven Fähigkeiten eines Menschen. Jede Aktion die ausgeführt oder durchdacht

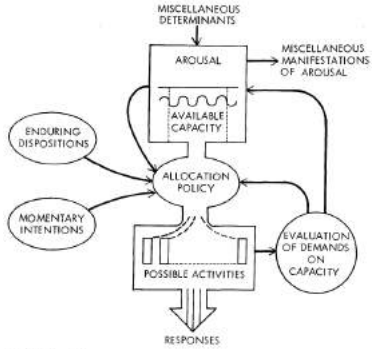


Abb. 2. Das Zusammenwirken von Aufmerksamkeit und dem Erregungszustand eines Menschen zur Bildung einer Entscheidung[2].

werden soll verbraucht Energie und Zeit. Bereits vermeidlich einfache Aktionen benötigen diese beiden Ressourcen. Deshalb muss es einen Mechanismus beziehungsweise ein Handlungsvorschrift geben, nach der die Ressourcen auf die unterschiedlichen Aufgaben verteilt werde. Diese Vorschrift heißt Aufmerksamkeit. Daniel Kahneman [2] beschreibt unterschiedliche Eigenschaften der Aufmerksamkeit.

Selektierungs-Eigenschaft der Aufmerksamkeit Alle Organismen, und somit auch Menschen, müssen unterscheiden, welche Stimulationen wichtig und welche unwichtig sind. Werden zwei Berührungen gleichzeitig wahrgenommen muss entschieden werden, welche Information Priorität hat. Geschiet dies nicht können unerwünschte Konsequenzen folgen. So muss in kürze entschieden werde, ob eine juckende Stelle nur ein unbedeutendes Haar oder ein giftiges Insekt ist. Diese Unterscheidungen benötigen ebenfalls Aufmerksamkeit.

Intensitäts-Eigenschaft der Aufmerksamkeit Die Aufmerksamkeit ist nicht entweder vorhanden oder nicht vorhandenen. Sie bewegt sich auf einem Spektrum. Kahneman[2] führt hierfür das Beispiel eines Schülers an, der dem Unterricht folgt. Es gibt für dem Schüler nicht die Möglichkeit seine vollständige Aufmerksamkeit auf den Unterricht zu lenken. Täte er dies hätte er keine Möglichkeiten mehr auf Änderungen in seiner Umgebung zu reagieren. Auch könnte er nicht entscheiden, wann es sinnvoll wäre, eine andere Aufgabe zu beginnen. Gleichzeitig kann er nicht dem Unterricht vollständig ignorant begegnen. Wenn er dies könnte müsste er gleichzeitig in der Lage sein seine Umgebung auszublenden. Dies wäre vergleichbar mit einem Ohnmachtsänlichen Zustand. Somit ist bei der Aufmerksamkeitssteuerung die Menge an Aufmerksamkeit, die einer Aufgabe zugeschrieben werden soll zu berücksichtigen. Wird einer Aufgabe zu viel Aufmerksamkeit zugeordnet, fehlen eventuell die Ressourcen bei einer dringlicheren

Aufgabe. Wird einer Aufgabe zu wenig Aufmerksamkeit zugeordnet, kann diese eventuell nicht oder nur zu langsam erfüllt werde.

Die Aufmerksamkeit wird in dieser Arbeit als menschliche Ressource aufgefasst, deren Verteilung es zu steuern gilt. Somit werden beispielsweise die Bereiche "Aspekte der Intensität"[2] und "Erregung"[2] ignoriert.

Eine Steuerung wird immer dann erreicht, wenn ein Stimulus verwendet wird, der die Aufmerksamkeit, eines Menschen, zu der gewünschten Information leitet. Diese Aufmerksamkeitssteuerung kann über jeden Sinn erfolgen. Beispiele wären das Ansprechen eines Menschen mit dem Namen und das Einblenden eines Warnsymbols im Auto. Vorweggreifend soll hier auch eine Anwendung, wie die Handyvibration nicht unerwähnt bleiben.

2.2 Überwachungsaufgaben

Überwachungsaufgaben fordern von dem Aufgaben-Ausführer, dass er über einen längeren Zeitraum Informationen aufnimmt und überwacht. Überwachen heißt dabei, dass der Aufgaben-Ausführer möglichst schnell auf Veränderungen reagieren kann. Ein Beispiel hierfür wäre ein Sicherheitsbeauftragter, der Überwachungsmonitore überprüft. Angenommen die Überwachung findet Nachts statt. Auszeichnendes Merkmal der Überwachungsaufgabe ist, in diesem Fall, dass der Großteil der Zeit der Großteil der Informationen unverändert bleibt. Im Gegensatz dazu steht die Überwachung bei Tag. Hier sind potentiell viele Veränderungen erkennbar, jedoch ist nur ein kleiner Teil für die Überwachungsaufgabe wichtig [3]. Dieses Beispiel zeigt, dass eine Differenzierung von Überwachungsaufgaben nötig ist um diese vereinfachen oder ermöglichen zu können.

Als allgemeine Ziele von allen Geräten, die Überwachungsaufgaben unterstützen lassen sich festhalten:

- Die Aufmerksamkeit des Aufgaben-Ausführers soll auf, für die Erfüllung der Aufgabe, relevante Informationen geleitet werden, ohne das es zu einer Ermüdung kommt.
- Es soll ermöglicht oder vereinfacht werden die Informationen in relevant und irrelevant zu unterteilen.

2.3 Haptische Schnittstellen

Der Mensch verfügt über einen Tastsinn. Um Informationen über diesen Sinn übertragen zu können, werden haptische Schnittstellen verwendet.

Die für den Tastsinn verantwortlichen Nervenzellen können auf unterschiedliche Arten stimuliert werden. Dementsprechen gibt es unterschiedliche haptische Aktuator, die zu Informationsübertragung verwendet werden können. Dabei ist ein Aktuator ein Bauelement, welches elektrische Signale in andere physikalische Größen, wie beispielsweise Bewegung, umsetzt. Dabei ist eine Unterscheidung zwischen Aktuator zu treffen. Die Kommunikation kann entweder über mechanische Bewegung oder elektrische Impulse erfolgen. Darüber hinaus lassen sich weitere Charakteristiken erkennen:

Für beiden Aktuator-Typen vergleichbar sind folgende Charakteristiken:

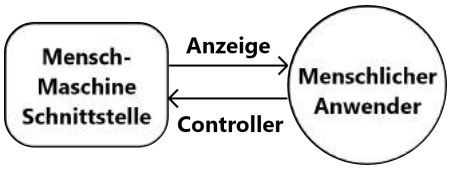


Abb. 3. Grundlegende Kommunikation zwischen Mensch und Maschine.[4]

– Position
  Die Position gibt den Ort der Stimulation durch den Aktuator an.Die Haut reagiert nicht an jeder Stelle gleich empfindlich auf haptische Stimulation[5, S. 91]. Die empfindlichsten Stellen liegen in den Fingerspitzen.
– Berührungsfläche Die Berührungsfläche gibt die vom Aktuator Stimulierte Fläche an.
– Dauer
  Die Dauer gibt die zeitliche Länge der Aktivierung des Aktuators an.

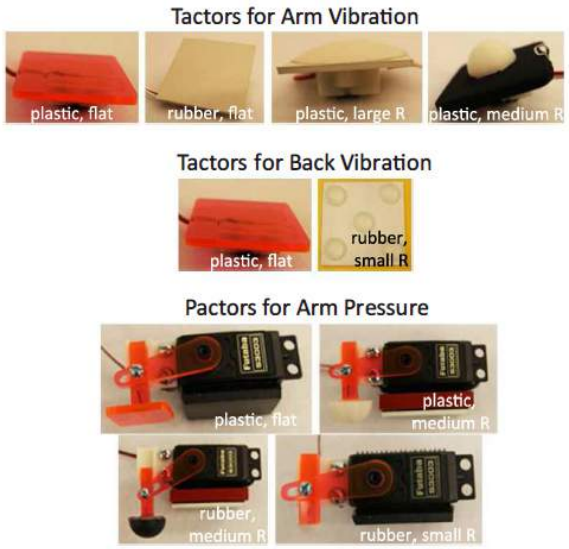


Abb. 4. Beispiele für haptische Aktuatoren[6]. Es liegt eine Unterscheidung von dem Verwendungszweck, dem verwendeten Material und der Form des Materials vor.

Für die Kommunikation über Vibrationen[5]:

– Frequenz

Die Frequenz gibt die Anzahl der Wiederholungen des Bewegungszyklus des Aktuators, über einen Zeitraum, an.
- Amplitude/Intensität
  Die Amplitude gibt das Ausrichtungsdelta des Aktuators an.

Für die Kommunikation über elektrische Impulse[7, S. 4]:

- Stromstärke
  Die Stromstärke mit der der elektrische Impuls versetzt wird.
- Spannung
  Die Spannung mit der der elektrische Impuls versetzt wird.
- Material
  Das Material gibt an, aus welchem Chemischen Stoff die Kontatkfläche des Aktuators aufgebaut ist.
- Feuchtigkeit
  Die Feuchtigkeit gibt die Menge an vorhandenem Wasser an der Kontaktfläche an. Dabei ist die Leitfähigkeit des Wassers der Grund für diese Charakteristik.

In beiden Fällen ist auch die Kombination der einzelnen Faktoren ausschlaggebend, wie effektiv die Kommunikation stattfindet. Dabei stellt jede Ausprägung dieser Kombinationen ein Aktivierungsmuster da. Diese Aktivierungsmuster werden von Menschen nicht nur mit unterschiedlichen Informationen, sondern auch mit subjektiven Emotionen belegt[8].

Ein Zusammenschluss von mehreren haptischen Aktuator führt zu einer größeren Anzahl von Einstellungsmöglichkeiten. Diese ermöglichen das übertragen von komplexeren Informationen im Vergleich zu einem haptischen Aktuator. Eine Alternative Einsatzmöglichkeit ist zu der Erhöhung der Redundanz bei der Informationsübertragung. Dabei senden die haptischen Aktuator, beispielsweise, alle das selbe Übertragungsmuster. Das zu erreichene Ziel ist hierbei dem Menschen, der haptische Aktuator auf der Haut trägt, die Aufnahme der Information zu erleichtern. Diese Anwendung ist gerade in kritischen Situationen,wie sie etwa in militärischen Einsätzen zu finden sind, hilfreich[9]. Nikolic et al. [9] beschreibt, wie haptische Aktoren Piloten bei der Überwachung von Flugzeugdaten unterstützen kann. Je nach Einsatzbereich können zusätzliche Einschränkungen gelten. In dem Bereits angesprochenen Militärbeispiel ist eine Verwendung von Aktoren, die an dem Finger angebracht sind, nicht sinnvoll. Ein Positionierung an den Fingern würde die Verwendung desselben einschränken.

3 Anwendungen

Nun stellt sich die Frage in welchen Ausprägungen diese Teilgebiete zusammengeführt werden können. Deshalb sollen im folgenden Anwendungen, die alle drei Teilgebiete umfassen beleuchtet werden.

3.1 Sinneswiederherstellung

Menschliche Sinne können, von Geburt an oder im laufe der Zeit, nicht, oder nur eingeschränkt, funktionsfähig sein. Um diesen Leistungsverlust ausgleichen zu können bedarf es technischer Hilfsmittel. Hierbei bietet die menschliche Haut eine Möglichkeit zur Aufnahme von Informationen, die typischerweise über andere Sinne aufgenommen werden würden.

Sehvermögen Nach dem Stand der Forschung ist das Auge das Leistungsstärkste Sinnesorgan, gemessen an der übertragenen Datenmenge[10]. Dabei liegt die absolute Leistung ca. bei der eines Ethernet-Kabels mit 10 Mbit/s[10]. Der Sehsinn kann somit bereits aus technischen gründen nicht vollständig über die Haut simuliert werden. Die für die Überwachung der Umwelt wichtigen Informationen lassen sich von den unwichtigen differenzieren.

Lesen Geschriebene Worte sind eine Darstellung der menschlichen Sprache. Im Fall der Einschränkung des Sehvermögens ist auch die Fähigkeit zu lesen beeinträchtigt.

Device	Function	Actuators	Display Location	Display Dimensions
Optacon[a]	Reading device for those with visual impairments	Piezoelectric bimorphs	Fingertip	24 × 6 pin array, vibrating at 230 Hz

Abb. 5. Rahmendaten des Optacons.[5]

Optacon Eine Lösung für diese Einschränkung wurde von Bliss et al. 1970 in Form des "Optacon" entwickelt (Zitiert nach:[5]). Dabei werden auf einer Anzeigefläche die Buchstaben in Form von Vibrationen dargestellt. Das identifiezieren der Buchstaben übernimmt ein Scanner, der über geschrieben Worte bewegt werden kann. Mit diesem Gerät ist war es möglich zwischen 50 und 100 Worte in der Minute zu lesen [5]. Bliss et al. [11] identifiert in seiner Arbeit drei Tests Charakteristiken, die einen Einblick in die Leistung eines "Direkt Übersetzers mit taktilem Ausgang"[11] bieten.

- Lesbarkeit
  Die Lesbarkeit beschreibt, mit welcher Wahrscheinlichkeit, die gelesene Information von dem Benutzer, wie vorgesehen interpretiert wird. Für das Erreichen der Charakteristik muss es möglich sein Buchstaben zu unterscheiden. Auch ist die Erneuerungsrate, mit dem das Gerät die Buchstaben neu zeichnet, von Bedeutung. Eine zu geringe Wiederholungsrate kann zu Missverständnissen führen.
- Lesegeschwindigkeit
  Die Lesegeschwindigkeit gibt an, wie schnell Wörter bzw. Buchstaben gelesen werden können. Diese Charakteristik hängt mit dem Trainingsstand des Anwenders zusammen.
- Lesbarer Ausschnitt
  In dem Lesbaren Ausschnitt können Buchstaben willkürlich erkannt werden. Je größer dieser Ausschnitt ist, desto länger kann ein Anwender lesen ohne Änderungen an einem Gerät vorzunehmen.

3.2 Zwischenmenschliche Kommunikation

Die Zwischenmenschliche Kommunikation ist ein komplexer Vorgang, bei dem zumeist viele Sinne beansprucht werden. Über den Hörsinn werden die Informationen aufgenommen, die in der gesprochenen Sprache zu finden sind. Der Sehsinn wird verwendet um Lippen zu lesen und somit ein besseres Verständnis zu erzeugen. Darüber hinaus kann über ihn die emotionale Lage des Gesprächspartners eingeschätzt werden und auf Gesten, wie ein Handschlag, reagiert werden. Jedoch gibt es auch Umgebungen, in denen diese Kommunikationswege unterbunden werden. Der Geräuschpegel kann zu hoch sein um Sprache zu verstehen. Die Lichtverhältnisse können zu dunkel sein um den anderen Menschen zu sehen, mit dem Kommuniziert wird [1].

Des weiteren können auch durch Unfälle, Alter oder Krankheiten die Augen und Ohren beeinträchtigt sein. Um die Fähigkeit der Zwischenmenschlichen Kommunikation zu erhalten sind Seh- und Hörhilfen verbreitete technische Werkzeuge. Eine weitere Alternative ist das Umverlagern der Kommunikation auf einen anderen Sinn[1].

Frank A. Geldard [1] beschreibt hierzu in seiner Arbeit die Entwicklung der Forschung, die versucht die zwischenmenschliche Kommunikation auf den Tastsinn zu verlagern. Zuerst wird beschrieben, wie die Haut dazu genutzt werden kann wie ein Ohr zu funktionieren. Dabei wird die Haut als Trommelfell verwendet. Dieser Ansatz liefert nach einer Einlernphase von 30h ein Vokabular von einigen einzelnen Worten[1]. Das Problem bei dieser Anwendung liegt in der Zuverlässigkeit. Bei einer Wiederkennungsrate von ca. 75

Tactons Die Idee, für die haptische Wahrnehmung spezialisierte Vibrationsmuster zu erstellen, wird von Stephen Brewster und Lorna M. Brown[12] behandelt. Ihr Vorschlag ist sogenannte Tactile Icons (Tactons) zu verwenden, die haptisch gut differenzierbar sind. Dabei orientieren sie sich an musik ähnlichen Mustern,

die von den taktilen Aktoren dargestellt werden[12]. Der Unterschied zu der Darstellung von Buchstaben ist, dass die Tactons selbst eine Bedeutung haben und nicht in eine gesprochene Sprache übersetzt werden müssen um sie zu verstehen. Dadurch sollte eine bessere Antwortzeit bei dem Benutzer erreicht werden. Wie in 6 sichtbar.

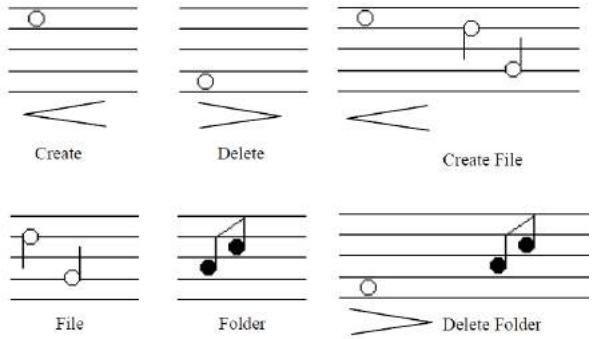


Abb. 6. Codierung von Informationen über einen Tacton[12]. Dabei wird eine Notation ähnlich zur Musik verwenet um Frequenz und Amplitude anzugeben.

3.3 Leistungssteigerung

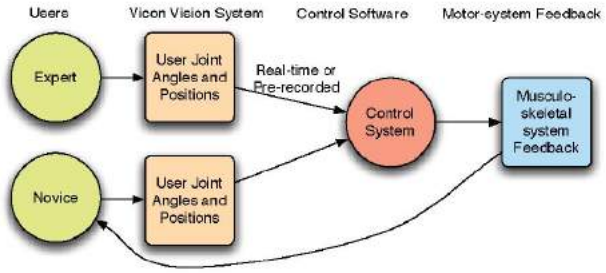


Abb. 7. Aufbau des Experiments zur Lehrnbeschleunigung durch haptische Schnittstellen[13].

Die Weitergabe von motorischen Fähigkeiten findet aktuell überwiegend visuell statt. So erhalten Sportler die meisten Informationen über den korrekten

Ablauf einer Bewegung über dem visuellen Abgleich von sich mit einem Lehrer. Um diesen vorgehen zu unterstützen haben Jeff Lieberman und Cynthia Breazeal[13] eine haptisch unterstützende Vorrichtung entwickelt. Dabei wird der Schüler, der die neue motorische Fähigkeit erlernen will, mit einem tragbarischen Feedback-System ausgestattet. In Abb. 7 ist das der Lernprozess beschrieben. Durch das System bekommt der Schüler direkt mitgeteilt, wenn er von dem vorgesehenen motorischen Ablauf abweicht. Dadurch bekommt er frühzeitig Feedback und gewöhnt sich keine falsche Bewegung an.

3.4 Erweiterung des Wahrnehmungsspektrums

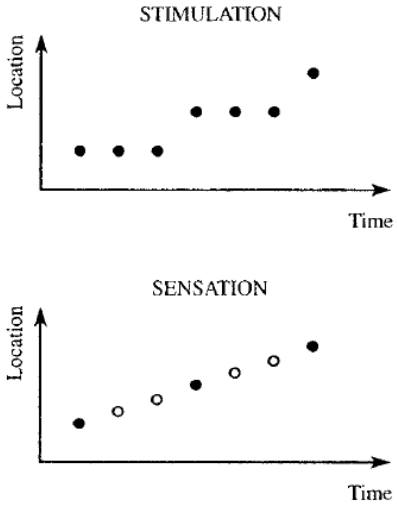


Abb. 8. Reale Stimulation im Vergleich mit der wahrgenommen Stimulation beim Auftreten der "Cutaneous rabbit" Illusion[4].

Haptische Illusion In 8 ist das Phänomen der "Cutaneous rabbit"[14] Illusion beschrieben. Die Illusion tritt auf, wenn unterschiedliche haptische Aktuatoren über die Haut verteilt sind. Falls diese in zeitlichen Abständen von ca. 40 msec bis 80 msec hintereinander aktiviert werden, wird die entstehende Stimulation nicht als viele einzelne Stimulationen sonder als eine durchgehende vernommen. Somit ist es möglich mit einem Aktuatoren-Feld, für den Menschen spührbare, "gerade"Linien zu erzeugen.

Navigationssysteme Abb. 9 zeigt, wie haptische Aktuatoren dazu verwendet werden können, um Himmelsrichtungen, auf der Haut, darzustellen. Dabei wird

11

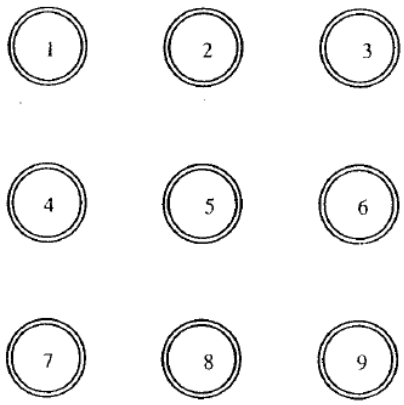


Abb. 9. 3x3 Aktuator-Feld zur haptischen Darstellung von Himmelsrichtungen[4].

"Norden" beispielsweise als die Aktivierung von $8 \rightarrow 5 \rightarrow 2$ codiert. Solche Anwendungen bieten die Möglichkeit ein intuitives Navigationssystem zu erstellen[15]. Die Illusion des "Cutaneous rabbit" kann hierbei verwendet werden um den Übergang zwischen den Aktuatoren flüssiger wirken zu lassen.

12

3.5 Zuverlässigkeit Erzeugung

Haptische Aktuatoren bieten die Möglichkeit Informationen redundant darzustellen. So können Informationen, die von einem Display abgelesen werden, zusätzlich haptisch unterstützt werden. Dies ist ein Vorgehen, dass bei Piloten zu dem Einsatz kommt. Anius H. Rupert[16] beschreibt in seiner Arbeit das Problem der räumliche Desorientierung bei Piloten, die keinen Horizont als Referenz zur Verfügung haben. Dies führt zu einem Verlust der Orientierung und somit zu einem Kontrollverlust über das Flugzeug. Eine Lösung Stellt das "Tactical Situation Awareness System (TSAS)"[16] da. Dabei wird der visuelle Horizont durch haptisches Feedback simuliert[16]. Im Falle einer visuellen Einschränkung ist der Pilot somit nicht mehr ausschließlich auf seine Augen beschränkt. Aus diesem Beispiel der Anwendung von Redundanz zu der Erhöhung der Zuverlässigkeit in Beobachtungsaufgaben lassen sich einige allgemeine Schlüsse ziehen:

Abb. 10. Ein Ansatz für die Beschreibung der Zusammenhänge von der Anzahl der angesprochenen Sinnen im Verhältnis zu der Zuverlässigkeit.

Um die Zuverlässigkeit des Systems zu erhöhen muss zuerst festgestellt werden auf welcher Seite des Spektrums das Problem liegt. Erhält der Anwender zu wenige, kritische, Informationen, muss dies durch hinzufügen von weiteren Anzeigen korrigiert werden. Findet hingegen eine Reizüberflutung statt, muss abgewogen werden. Wenn Informationen, ohne Risiko, ausgelassen werden können ist dies die beste Antwort auf das Problem. Ansonsten muss wie bei TSAS gesehen eine Komponente hinzugefügt werden, die eine Aufmerksamkeitssteuerung vornimmt.

4 Selbstständigkeitserklärung

Ich versichere hiermit, dass ich die vorliegende Arbeit selbstständig verfasst, und weder ganz oder in Teilen als Prüfungsleistung vorgelegt und keine anderen als die angegebenen Hilfsmittel benutzt habe. Sämtliche Stellen der Arbeit, die benutzten Werken im Wortlaut oder dem Sinn nach entnommen sind, habe ich durch Quellenangaben kenntlich gemacht. Dies gilt auch für Zeichnungen, Skizzen, bildliche Darstellungen und dergleichen sowie für Quellen aus dem Internet.

Name: Leon Huck

Titel der Arbeit: Aufmerksamkeitssteuerung durch Haptische Schnittstellen in Beobachtungsaufgaben

Ort, Datum: Karlsruhe, den 30.08.2019

14

Literatur

1. Frank A. Geldard. Some neglected possibilities of communication. *Science*, 131(3413):1583–1588, 1960.
2. Daniel Kahneman. *Attention and effort*, volume 1063. Citeseer, 1973.
3. Angus Craig. Nonparametric measures of sensory efficiency for sustained monitoring tasks. *Human Factors*, 21(1):69–77, 1979. PMID: 468268.
4. Hong Z. Tan and Alex Pentland. Tactual displays for sensory substitution and wearable computers. In *ACM SIGGRAPH 2005 Courses*, SIGGRAPH '05, New York, NY, USA, 2005. ACM.
5. Lynette A. Jones and Nadine B. Sarter. Tactile displays: Guidance for their design and application. *Human Factors*, 50(1):90–111, 2008. PMID: 18354974.
6. Y. Zheng and J. B. Morrell. Haptic actuator design parameters that influence affect and attention. In *2012 IEEE Haptics Symposium (HAPTICS)*, pages 463–470, March 2012.
7. K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins. Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE Transactions on Biomedical Engineering*, 38(1):1–16, Jan 1991.
8. M. A. Baumann, K. E. MacLean, T. W. Hazelton, and A. McKay. Emulating human attention-getting practices with wearable haptics. In *2010 IEEE Haptics Symposium*, pages 149–156, March 2010.
9. Mark I Nikolic, Aaron E Sklar, and Nadine B Sarter. Multisensory feedback in support of pilot-automation coordination: the case of uncommanded mode transitions. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 42, pages 239–243. SAGE Publications Sage CA: Los Angeles, CA, 1998.
10. Kristin Koch, Judith McLean, Ronen Segev, Michael A. Freed, I. I. Berry, Michael J., Vijay Balasubramanian, and Peter Sterling. How ¡em¿much¡/em¿ the eye tells the brain. *Current Biology*, 16(14):1428–1434, June 2019.
11. J. C. Bliss, M. H. Katcher, C. H. Rogers, and R. P. Shepard. Optical-to-tactile image conversion for the blind. *IEEE Transactions on Man-Machine Systems*, 11(1):58–65, March 1970.
12. Stephen Brewster and Lorna M. Brown. Tactons: Structured tactile messages for non-visual information display. In *Proceedings of the Fifth Conference on Australasian User Interface - Volume 28*, AUIC '04, pages 15–23, Darlinghurst, Australia, Australia, 2004. Australian Computer Society, Inc.
13. Jeff Lieberman and Cynthia Breazeal. Development of a wearable vibrotactile feedback suit for accelerated human motor learning. In *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pages 4001–4006. IEEE, 2007.
14. Frank A Geldard and Carl E Sherrick. The cutaneous"rabbit": A perceptual illusion. *Science*, 178(4057):178–179, 1972.
15. Hong Tan, Robert Gray, J Jay Young, and Ryan Taylor. A haptic back display for attentional and directional cueing. *Haptic*, 2003.
16. Angus H Rupert. An instrumentation solution for reducing spatial disorientation mishaps. *IEEE Engineering in Medicine and Biology Magazine*, 19(2):71–80, 2000.