Artificial Skin in Robotics

A Comprehensive Interface for System-Environment Interaction

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München, den 26. April 2012

Michael Strohmayr

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Zusammenfassung

Die Roboter kommen[1] - damit ist nicht eine martialische Invasion durch Roboter wie in der Science Fiction gemeint, sondern die Entwicklung, dass moderne Robotersysteme zunehmend ihren abgeschotteten Arbeitsraum verlassen und auch physikalisch mit dem Menschen interagieren. Entfallen die räumlichen Barrieren zwischen dem Arbeitsraum des Menschen und dem des Robotersystems, müssen neue Sicherheits- und Bedienkonzepte für die physikalische Interaktion entwickelt werden. Es muss sichergestellt werden, dass beispielsweise bei der gemeinsamen Montage innerhalb einer Fahrzeugkarosserie oder bei der Zusammenarbeit in der Enge eines Operationssaals keine Gefahren entstehen. Sensorik ist dabei der Schlüssel um Veränderungen der Umgebung und Aktionen des Menschen zu erfassen. Ein Teilaspekt dabei ist das Erkennen des direkten physikalischen Kontakts des Roboters mit seiner Umgebung bzw. mit dem Menschen. Um die Sicherheit von Mensch und Roboter zu gewährleisten, ist eine lückenlose Überwachung der Außenhülle des Robotersystems auf Kontakte wünschenswert. Eine vielversprechende Lösung hierfür sind taktile Sensoren, die direkt auf der Außenhülle des Robotersystems angebracht sind. Die Messdaten taktiler Sensoren können genutzt werden, um beispielsweise adäquat auf eine Kollision zwischen Medizinroboter und Patient zu reagieren oder um eine intuitive Interaktion bei Montageaufgaben zu ermöglichen. Eine Herausforderung für die Entwicklung taktiler Sensoren ist die Adaption auf komplexe, oftmals mehrfach gekrümmte Oberflächen, die mit den derzeit verfügbaren taktilen Sensoren nicht, oder nur unzureichend, möglich ist. Die Analyse des Standes der Technik zeigt, dass die verwendeten Materialien und Herstellungsverfahren die Mehrzahl der verfügbaren taktilen Sensorsysteme auf die Anwendung auf planaren oder einfach gekrümmten Oberflächen beschränken. Agieren Roboter in der unstrukturierten und zeitveränderlichen Umgebung des Menschen, sind Kollisionen nicht immer vermeidbar. Daher muss u.a. die Oberfläche des Robotersystems so gestaltet sein, dass die Folgen einer Kollision abgeschwächt werden. Eine nachgiebige mechanische Dämpfungsschicht auf der Oberfläche des Roboters

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[1] Titel des Ressorts *Wissen*, *Die Zeit* in der Ausgabe N° 4 vom 19. Januar 2012

ist eine denkbare Lösung. Um die Feinfühligkeit der taktilen Sensoren durch die Dämpfungsschicht nicht zu beeinträchtigen ist es vorteilhaft, die Sensorelemente außen auf der Dämpfungsschicht zu integrieren. Als Konsequenz müssen jedoch solche taktilen Oberflächensensoren – um bei Kollisionen nicht zerstört zu werden, elastisch verformbar und überlastfest gestaltet sein. Zentraler Aspekt bei der Entwicklung von taktilen Sensorsystemen war in der Vergangenheit meist die Feinfühligkeit sowie eine möglichst hohe räumliche Auflösung. Aspekte wie die spätere Integration in ein Robotersystem und die Überlastsicherheit wurden oft vernachlässigt. Wird hingegen die Entwicklung auf Robustheit hin ausgerichtet, so fehlt es den resultierenden Sensorsystemen zumeist an der nötigen Feinfühligkeit. Der Stand der Forschung zeigt eindrucksvoll, dass isoliert betrachtet jede einzelne der gewünschten Eigenschaften optimiert erreicht werden kann – nicht jedoch deren Kombination. Der Fokus dieser Arbeit liegt daher auf der Lösung des Zielkonfliktes zwischen hoher Messempfindlichkeit und mechanischer Robustheit. Angelehnt an die Funktionalität der menschlichen Haut sollen – neben den multimodalen sensorischen Eigenschaften – mechanische Verformungs- und Dämpfungseigenschaften realisiert werden, sowie die Einflüsse eines solchen Oberflächensensorsystems auf die Thermoregulation berücksichtigt werden. Ausgehend von der Analyse des Standes der Technik und den aktuellen Forschungsarbeiten, sowie den Ergebnissen eigener Vorarbeiten werden Entwurfsparadigmen vorgeschlagen, welche die Lösung des Zielkonflikts zwischen Messempfindlichkeit und Robustheit erleichtern. Die Entwicklung sowie die Struktur der Arbeit sind an die in VDI-Richtlinie 2206 vorgeschlagene Entwicklungsmethodik für mechatronische Systeme angelehnt. Hierin wird das V-Modell aus dem Softwareengineering auf die Entwicklung mechatronischer Systeme angepasst. Im Rahmen des Systementwurfs wird ein Gesamtkonzept für eine skalierbare künstliche Haut für Robotersysteme erarbeitet, sowie ein innovatives Konzept für die benötigte Sensordatenverarbeitung vorgeschlagen. Neben der Skalierbarkeit von Sensorfläche, räumlicher Auflösung und Messempfindlichkeit, wird die Skalierbarkeit der benötigten Herstellungsverfahren berücksichtigt. Angelehnt an die Partitionierung in der Softwareentwicklung wird das gewünschte Funktionsspektrum der künstlichen Haut in parametrierbare funktionale Komponenten unterteilt. Während des domänenspezifischen Entwurfs werden – basierend auf der integrativen Entwicklung von maßgeschneiderten Materialien und skalierbaren Herstellungsverfahren – Lösungen für die Umsetzung der einzelnen funktionalen Komponenten erarbeitet. Beispielsweise werden neuartige elektrisch leitfähige Leiterbahnen auf Polymerbasis entwickelt, um die geforderte elastische Verformbarkeit der Sensorfläche zu ermöglichen. Die Eigenschaften des geplanten Gesamtsystems können durch die Modellbildung und Simulation der einzelnen funktiona-

len Komponenten abgeschätzt werden. Für die Verifikation der gewünschten Eigenschaften wird, da derzeit kein standardisiertes Testverfahren für taktile Sensoren zum Einsatz auf Robotersystemen existiert, ein im Rahmen dieser Arbeit entwickeltes einfaches Testverfahren verwendet, welches erstmalig eine Vergleichbarkeit unterschiedlicher taktiler Sensorsysteme ermöglicht. Im Rahmen der Systemintegration wird exemplarisch ein taktiler Oberflächensensor mit Auswerteelektronik zur Erfassung von Normalkräften realisiert. Hierzu werden die benötigten funktionalen Komponenten kombiniert, sowie die erforderlichen Herstellungsprozesse und Materialien erprobt und prototypisch umgesetzt. Die Prototypen der künstlichen Haut werden auf einem eigens entwickelten Teststand identifiziert und deren Praxistauglichkeit anhand von Versuchen zur Kollisionsdetektion mit einem DLR Leichtbauroboter demonstriert. Die durchgeführten Untersuchungen zeigen, dass mit dem vorgeschlagenen Gesamtkonzept eine bezüglich Sensorfläche, räumlicher Auflösung und Messempfindlichkeit skalierbare künstliche Haut für Robotersysteme realisiert werden kann. Die Prototypen und Experimente zeigen, dass diese künstliche Haut auf mehrfach gekrümmten, nachgiebigen Oberflächen eingesetzt werden kann und der Zielkonflikt zwischen Messempfindlichkeit und Robustheit gelöst wurde.

Abstract

Modern robotic systems are gradually escaping their fenced workspace and begin to physically interact with humans. If the physical barriers between the workspace of the robotic system and the human fall away, new safety and interaction concepts for the physical human robot interaction have to be developed. These concepts have to make sure, that, e.g. during a joint assembly task within a car body neither the human nor the interacting robotic system are endangered. Sensor systems are a key element to detect changes in the environment and sense actions of the human user. One aspect herein is the detection of direct physical contact between the robotic system and the environment or the human user. In order to ensure safety of human and robotic system a close surveillance of the covering structure of the robotic system with respect to physical contact is desired. A promising solution are spatially distributed tactile sensors that are mounted on the covering structure of the robotic system. The acquired tactile information can be utilized to initiate adequate collision reaction strategies or as a means of intuitive human machine communication. A major challenge for the development of tactile sensors for robotic systems is the adaptation to the complex, often 3D-curved surfaces of modern robotic systems. This adaptation is not or only insufficiently possible with the available tactile sensors. The analysis of the state-of-the-art reveals, that the applied materials and manufacturing technologies restricts the majority of tactile sensors to the application on planar or developable surfaces.

If robotic systems operate in an unstructured and time varying environment collisions can no longer be avoided. That is why, amongst other means, the surface of the covering structure of the robotic system has to be equipped with a passive mechanical damping layer. In order not to constrain the sensitivity of the tactile sensors, the tactile sensors have to be integrated on top of the mechanical damping layer. Consequently, the tactile surface sensors have to be stretchable to allow for the underlying mechanical damping layer to deform in case of a collision. In addition, the tactile surface sensors have to be overload proof to withstand the high indentation forces that occur in case of a collision. In the past, the majority of approaches towards tactile sensors for robotic systems focussed on high spatial resolution and sensitivity. A future integration into a robotic system or the mechanical robustness of the tactile sensors have often been neglected. However, if the development was focussed on mechanical robustness, the resulting tactile sensors lack the required sensitivity. The analysis of the current state-of-the-art of science and technology impressively shows that, considered individually, all requirements can be fulfilled – but not their combination.

Therefore the focus of this thesis is the derivation of a solution of the goal conflict between the desired high sensitivity and the required mechanical robustness. Human skin is considered as a design metaphor for the development of a multi functional artificial skin concept that, next to providing the required sensory capabilities, exhibits mechanical deformation and damping properties required for the operation on a robotic system. Based on the analysis of the current state-of-the-art of science and technology and the outcome of own previous work design paradigms for the solution of the described goal conflict are proposed. The development and the structure of this thesis are based on the design methodology for mechatronic systems presented in VDI 2206. Herein the V-model, known from software engineering, is adapted for the development of mechatronic systems. During the system design an overall concept for a scalable artificial skin is derived. The concept allows the adaptation of the properties of the artificial skin to the respective application site on the robotic system. Besides the scalability of sensor surface area, spatial resolution and sensitivity the pursued approach accounts for scalability of the underlying manufacturing processes that is required for the successful integration into robotic systems. In addition, a concept for the acquisition and preprocessing of the tactile data is proposed. Based on the functional partitioning, known from software design, the desired functional range of an artificial skin is divided in adjustable functional components. During the domain specific design concepts for the individual functional components are derived based on the integrative design of tailored materials and scalable manufacturing processes. As an example, novel electrically conductive polymer based circuit tracks are developed in order to enable the required elastic deformability of the sensitive surface area of the artificial skin. The properties of a future artificial artificial skin system can be anticipated based on the conducted FEM simulation.

Currently no standardized test procedure for the assessment of the functionality of tactile sensor exists, therefore a simplified test procedure for the verification of the desired properties of the artificial skin is proposed. Within the system integration exemplarily a tactile surface sensor for the acquisition of normal indentation forces is implemented. For this, the required functional components are combined and the underlying manufacturing processes are field-tested. The resulting artificial skin prototypes are identified on a specialized testbed and applied on a robotic system. The suitability for daily use of the artificial skin prototypes is examined in a collision detection scenario on the DLR LWR III. The conducted tests demonstrate, that the proposed overall design concept allows for the development of an artificial skin that is scalable with respect to sensor surface area, spatial resolution and sensitivity. The prototypes and the conducted experiments verify that the presented artificial skin can be operated on 3D-curved surfaces of modern robotic systems and that the goal conflict between sensitivity and a collision tolerant design can be solved.

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Introduction

Today, various technical systems make use of tactile information. Ranging from touch displays in modern cell phones to in-shoe measurement of pressure distribution for the design of orthopedic insoles for running shoes. Tactile sensors in general provide information regarding physical contact between different systems. In the context of robotic systems tactile sensing can be defined as the acquisition of information from tactile sensors located in or on the structure of a robotic system. The definition of tactile sensors is not always consistent in literature, therefore the definitions that are applied for this thesis are outlined in the following section.
"Tactile sensors" are defined according to Lee and Nicholls [86] "as a device or system that can measure a given property of an object or contact event through physical contact between the sensor and the object". The success of electronic consumer goods, e.g. smart phones, is, amongst other factors, based on the introduction of touch sensitive displays. The touch sensitive displays make use of multiple interaction channels. For close interaction tactile input is combined with visual output. By capturing the motion of one or multiple fingers on the touch screen, intuitive interaction is possible and reduces the barriers of user acceptance. The introduction of an intuitive HMI might have the same effect on physical interaction between human users and robotic systems and thus may help to facilitate the introduction of robots into our everyday environment.

Depending on the application site in the robotic system tactile sensors can be subdivided into intrinsic and extrinsic tactile sensors, see e.g. Tegin and Wikander [162]. This subdivision follows the definitions often applied for human sensation: haptic sensation consists of kinesthetic and tactile sensation, where kinesthetic sensations originate from sensory cells in muscles and joints and tactile sensation stems from the sensory cells in human skin. Both sensor categories contribute to the sensation that is evoked by a physical contact. When we lift an object from a table the kinesthetic sensors provide information regarding the joint angles and muscle activation whereas the tactile sensors in the skin of the human hand provide information regarding the contact with the grasped object.

Similarly the intrinsic sensors that are located within the kinematic chain of the rigid mechanic structure of a robotic systems, see figure 1.1(a), provide information regarding the joint angles and torques that are applied in the robotic system. The information regarding the resulting forces and torques is viable for the control of the robotic system. According to Cutkosky et al. [146] P.456, intrinsic sensors can be defined as "devices that measure an average or resultant quantity". For intrinsic sensors often metal structures equipped with strain gages are utilized. The application of standardized precision elements enables highly accurate acquisition of the forces and torques exerted on the structure of the robot. The technical equivalent to the sensory cells of human skin is referred to as extrinsic tactile sensors, see figure 1.1(b). Extrinsic tactile sensory provide information about the spatial distribution e.g. of the pressure at the contact surface resulting from the physical interaction with an object. According to Tegin and Wikander [162], an extrinsic

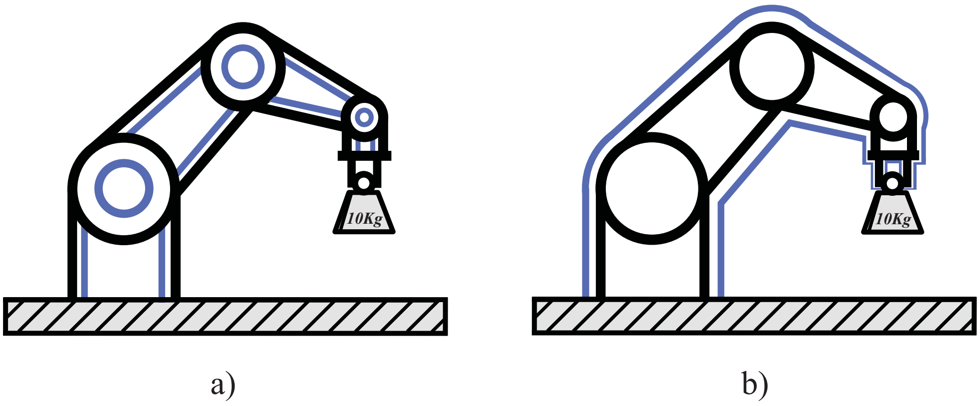


Figure 1.1: Classification of tactile senors, a) intrinsic sensors within the kinematic chain of the robot, b) extrinsic tactile sensors on top of the covering structure of the robot

tactile sensor "typically senses normal forces and contact positions". Tactile sensing is, according to Harmon [50], beneficial for robotic systems in various contexts. According to [146] P.456, (dexterous) manipulation, exploration and response are supported by tactile sensors.

1.1 Tactile sensing in robotic applications

In the context of robotic hands extrinsic tactile information can be applied for grip force control, multi-fingered manipulation and for robotic haptic exploration of unknown environments. Okamura and Cutkosky [111] present an algorithm for the detection of surface features for robotic haptic exploration based on tactile sensor data. If applied to the complete surface of a robot, extrinsic tactile senors are able to enhance robot "self awareness". Extrinsic tactile information can help to enable safe human robot interaction as collisions can be detected and safe reaction strategies can be activated. Therefore extrinsic tactile sensors can help to further the capabilities of robots to discriminate between unintentional collision and intended physical human robot interaction. An other field for the application of tactile sensors in robotic interaction is robotic manipulation. According to [146] P.353, "Most robot manipulation and assembly tasks would benefit from the utilization of tactile sensory information". Okamura et al. [112] present an overview of dexterous robotic manipulation and define contact models between different types of robotic fingertips. Amongst others following modalities of an external mechanical stimulus are important for robotic manipulation tasks:

- Contact detection
- Pressure distribution
- Slip detection

The event of making and breaking of physical contact can be applied in order to determine if an object actually resides in a closed gripper or has been released. The evaluation of the pressure distribution can be applied in the determination of the curvature of an object in contact with the tactile sensor. The detection of slip can be applied for autonomous grasp force adjustment during robotic manipulation.
Robotic exploration tasks can be supported by tactile information regarding:

- Object shape
- Object hardness / elasticity
- Surface roughness

Cutkosky et al. [146] P.459 even suggest to include temperature sensors equipped with a heating device in order to acquire the thermal conductivity and heat capacity of the object in physical contact with the tactile sensor.

1.1.1 Industrial joint assembly tasks

Figure 1.2: Intuitive human robot interaction, during the completion of a joint assembly task. Photograph courtesy of S. Parusel

The habitat of robots in industrial application has been and often still is exactly structured and demarcated with high physical or optical fences. Industrial robotic systems are kept enclosed in cages like dangerous predators in zoos. The workspace of the robots is cleared and closely monitored with emergency stops and fences to prevent the entrance of human users into the robot workspace. The complexity of highly integrated mechatronic products results in demanding assembly processes. Joint human-robot assembly tasks are designed, e.g by Reinhart et al. [125] and Lenz et al. [88], to combine the strength of robotic systems with the flexibility of human personnel, see figure 1.2. If human workers can enter the workspace of a robotic system physical interaction can occur accidentally in the form of collisions, or intentionally as desired physical Human Robot Interaction (pHRI). Thus, the established paradigm defining a robot's workspace as a no-go area for humans is becoming outdated. The co-existence of humans and robots in the same workspace requires additional information for the control of safe interaction. Before humans can be allowed to enter the active workspace of robotic systems the effects of un-

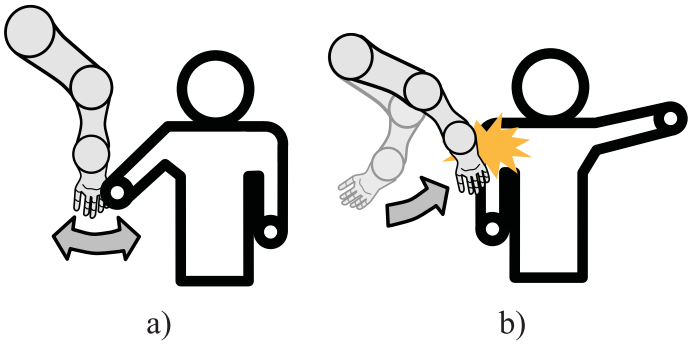


Figure 1.3: Intended human robot interaction and unintended collision.

intentional collisions have to be analyzed. Therefore Haddadin and colleagues, e.g. [46] have conducted an assessment of the severity of collisions between robots and humans. It has been shown, that the severity of collision can be reduced if appropriate collision reaction strategies are applied.

Vision based surveillance systems are commercially available, but close interaction in restricted workspaces often results in occlusion of the cameras and thus in decreasing reliability of vision based scene surveillance. Therefore, additional information from sensor systems that are not obstructed by close interaction is required in order to enable the discrimination between intended pHRI, figure 1.3(a) and unintended collision, figure 1.3(b). Tactile sensors provide information regarding the spatial distribution of an indentation force and thus can contribute to a safe pHRI and the design of intuitive human machine interfaces (HMI).

Today, the physical interaction between human user and robotic system, e.g. for user guided trajectory teaching, is often restricted to the control panel or the robot end-effector as interaction area. These interaction areas can be equipped with sensors that enable the acquisition of the forces and torques during physical interaction. Commonly force-torque sensors are located between the robot end-effector and the attached tool. An example of a pHRI is presented by Voyles and Khosla [170] who apply a force torque sensor at the robot tool center point to modify the motion trajectory of a robotic manipulator.

Only recently, physical interaction between human user and the entire mechanical structure of a robot based on data from intrinsic joint torque sensors is being investigated by Haddadin et al. [48]. The presented approach towards safe pHRI is based on contact information derived from the intrinsic sensors of a DLR lightweight robot (LWRIII) and allows the human user to utilize the entire structure of the LWRIII as HMI.

To further the ability of robots to physically interact with their environment, e.g. to enable the detection of multiple simultaneous contacts, the sensory capabilities of the robot can be enhanced by the introduction of tactile sensors on the surface of the robot structure. One approach towards pHRI based on extrinsic tactile sensors that are distributed on the robot surface is presented by Wösch and Feiten [183]. Based on the data gathered by the tactile sensors covering almost the entire surface of the robot different reaction strategies for pHRI are implemented.

1.1.2 Service robotics in unstructured environments

Figure 1.4: The DLR Justin, a humanoid robotic system for service robotics in unstructured environment, e.g. Ott et al. [114]

The introduction of robots into human every day environment has been predicted for a long time. Elderly care or household robotics, see figure 1.4, are only two popular scenarios for the desired interaction of humans and robots in the same workspace. The recent increase in the number of humanoid robots which are capable of robust physical interaction with their environment demonstrates the potential of service robotics in human everyday environment. This environment is subject to continuous change, objects can be introduced in and removed from the robot workspace at any time. Thus, robots for the application in human every day environment have to be able to operate in unstructured environments. Collision-free manoeuvering and object manipulation in an unstructured environment can be based on the acquisition of extensive sensory information. The sensor data processing and the planning of the required trajectories is time consuming and constrains the velocity of the moving robotic system.

A successful introduction of robots into the human environment requires that neither the human user nor objects in the environment are harmed or damaged by the robotic system. Therefore passive and active collision detection as well as reaction strategies are required. In order to reduce collision severity the skeletal structure of a robot can be designed to be passively compliant, and thus collision tolerant, e.g. Grebenstein et al. [45]. In addition the covering structure of robotic systems can be equipped with a passive mechanically damping covering. Park et al. [116] evaluate the design of mechanical damping layers to cover robotic systems. The authors conclude, that the severeness of collisions can be reduced if a passive mechanical damping layer is applied on the robot surface.

Active collision reaction can be based on input from the intrinsic sensors of the robotic system. The detection of a contact triggers an active reaction strategy, that activates e.g. the brakes of the manipulator or changes the control mode of the robotic system. The combination of passive collision tolerant design and active sensor based collision reaction strategies enables robotic systems that are capable to manoeuver in unstructured environment without too much constraints with respect to manoeuvering velocity.

A second important aspect for the introduction of tactile surface sensors is the dexterity of robotic manipulators. For a service robotic scenario the manipulation of objects is quintessential. The majority of the objects in human everyday environment are designed to be manipulated by the human hand. To promote robotic dexterity towards the manipulation of fine and fragile objects, dexterous robotic hands e.g. the DLR-Hand-II presented in Butterfass et al. [11] as well as extensive sensory input is required.The application of tactile sensors on robotic hands may help to further increase the dexterity with respect to object manipulation.

The introduction of robotic systems into care facilities for the elderly is propagated especially in robot-affine countries like Japan. The potential of robotic systems in elderly care scenarios has been demonstrated in recent studies, e.g. by Wada et al. [171]. The authors present a robot seal that actively interacts with the elderly, and shows promising results especially with patients suffering from dementia. Tactile sensors below the artificial fur enable an adequate reaction to the physical input.

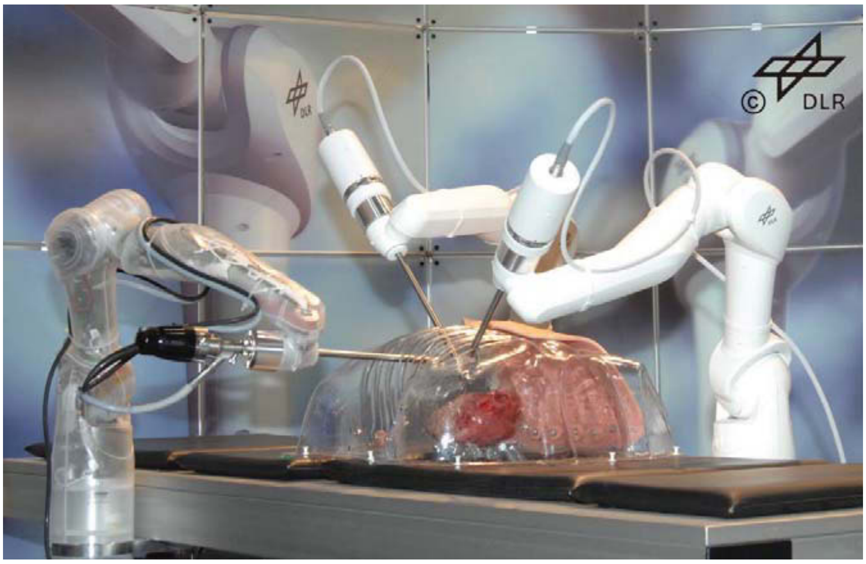


Figure 1.5: The DLR Mirosurge setup for robotic minimally invasive surgery, e.g. Hagn et al. [49]

1.1.3 Medical robotics

The application of robotic systems in the medical context is currently intensively investigated by various research groups and propagated by suppliers of medical equipment. Today, robot assisted or robot-based surgical intervention is no longer science fiction. Tele-manipulated robotic surgery systems have become standard for a set of surgical procedures. Especially, for so called minimally invasive surgery (MIS) the introduction of tele-manipulated robotic surgery systems is supposed to revolutionize the way the surgeon works. Moorthy et al. [100] investigated the impact of enhanced dexterity provided by robotic instruments in a robot based surgical setup. The authors conclude that the dexterity is enhanced and the number of errors reduced in tele-operated robot based surgery.

The introduction of robotic systems into the operating room results in an even further restriction of the space where surgeon and staff are able to manoeuver. Similar to the pHRI in an industrial environment the interaction between operating room (OR) staff and robotic systems in the constrained space of the operation room is prone to unintended collisions. The close interaction of robot, surgeon, staff and patient requires an even higher level of safety measures as unintended collisions might affect the progress of the intervention and the patient's health. The physical interaction can be subdivided in extracorporal and intracorporal interaction. The extracorporal interaction manly concerns surgeon and staff. For this interaction the same safety enhancing strategies based on passive and active collision severeness reduction as in industrial context can be applied.

For the intracorporal interaction between robot and patient special attention has to be paid in order to ensure the patient's safety. In a minimally invasive operation scenario the operation situs, e.g. the abdominal cavity, is no longer accessible for the hands of the surgeon; the introduction of stick-like hand guided instruments is required. This results in a loss of tactile feedback and offers only limited kinesthetic feedback. Thus, basic surgical skills, e.g. the manual palpation of tissue e.g. for the localization of tumors within healthy tissue are impaired.

The introduction of minimally invasive robotic surgery (MIRS), see e.g. figure 1.5 allows the surgeon to command the movement of robot guided instruments from an input station that enables an ergonomic working position and provides 3D visual feedback from the intervention site, e.g. Hagn et al. [49]. Similar to conventional MIS the introduction of MIRS results in the loss of haptic and tactile feedback for the surgeon. For the restoration of kinesthetic feedback a MIRS system is presented by Hagn et al. [140] that provides haptic force/torque feedback based on a miniaturized 6 degree of freedom (DOF) force torque sensor (FTS) at the tip of the robot guided instruments, e.g. Thielmann et al. [164]. The robot guided tissue palpation presented by Seibold [141] is based on the sequential palpation of discrete points of interest on the tissue surface. The acquired reaction forces offer a high accuracy for each palpation point and are applied to compute a tactile map of the region of interest. The major drawback of the sequential data acquisition is the inherent discretization. Especially, small tissue alternations, e.g. ulcers may not be identified if located between two discrete palpation points. Increasing the accuracy of the palpation requires an increase of the number of discrete palpation points and thus results in an increase of time required for the palpation.

These drawbacks may be countered by the introduction of spatially distributed tactile sensors on the tips of the robot-guided instruments that enable a simultaneous palpation of the region of interest. A spatially distributed tactile sensor for tissue palpation with a surgical forceps is presented by Schostek [137]. This system offers a high spatial resolution but is limited with respect to sensor size. The maximum area that can be palpated at a time is $8.4mm \times 13.5mm$. Therefore objects larger than the sensitive surface again require sequential palpation of the region of interest. The size of the sensitive surface is restricted by the diameter of the point of entry for the MIS instruments, the so called trocar. The development of spatially distributed tactile sensors that allow for the simultaneous palpation of a region of interest larger than the diameter of the trocar and offering a sensitivity similar to the human fingertip would be desirable. A deformable tactile sensor would be required for the instrument to fit through the trocar.

1.2 Problem Statement

In 1982 Leon Harmon [50] stated, that "Touch sensing, [...], can be expected to evolve into a highly developed technology in the near future, closely paralleling automated vision capability". While artificial vision technology has long since matured and provides off-the-shelf solutions for robotic application, after more than thirty years of research, covering a robot entirely with a touch sensitive cover is still far from being standard. The essential question is:

> What prevents the success of tactile sensors in robotic applications?

A possible answer to the above question may be found in the direction of the research activities in tactile sensing. Only recently, the focus of the development of tactile sensors for robotic fingers and grippers shifted to the design of touch sensitive covers for the entire structure of a robotic system. A likely reason is that the workspaces of humans and robotic systems have been consequently separated from each other and a touch sensitive cover for the entire surface of the robotic system just has not been necessary. Moreover, many of the basic approaches and solution principles for tactile sensors have been published in the late eighties and early nineties, this "ancient" knowledge often is neglected by young researchers that are new to the field of tactile sensing, (this includes the author at the beginning of this thesis, see section 3.2.7). The analysis of the literature regarding tactile sensors reveals, that the probability is pretty high, that today's "new" transduction principles that are presented in "innovative" tactile sensor prototypes have already been proposed in the eighties and nineties of the last century. As a result the focus on the transduction properties which, according to Dahiya et al. [20] still is the basic motivation for the development of tactile sensors prevents the shift towards the development of implementable tactile sensor systems. A possible reason may be found in the requirements defined for tactile sensor systems. Originally introduced by Harmon [50] these requirements are based on the results of the analysis of questionnaires sent to about fifty persons ranging from students to specialists in robotics. One of the central questions was: "What would you like to see available ("blue sky") in tactile-sensing devices?" The answers to this open question can be summarized as:

- Compliant and durable surface
- $1mm$ to $2mm$ spatial resolution
- $1g$ to $10g$ minimum sensitivity
- $1000:1$ dynamic range

- Monotonic output
- At least $100Hz$ frequency response
- High stability and repeatability
- Low hysteresis

Over the years these high expectations for the properties of an ideal sensor have been converted to "general requirements" for tactile sensors. This process motivated and still motivates researchers to develop new prototypes of tactile sensors aimed at the fulfilment of the above quoted benchmark. As a result tactile sensors are often presented as laboratory prototypes of tactile sensor systems in different stages of integration. The challenge of the later spatial and functional integration of tactile sensors has long since been identified to be hindering the successful introduction of tactile sensors as a standard component for robotic systems, Jacobsen et al. [57] or Cutkosky et al. in [146]. Dahiya et al. [20] point out, that "one should aim for the tactile sensing system" and that "Much work needs to be done at the system level before artificial touch can be used in a real-world environment". An insight the authors of Jacobsen et al. [57] already emphasized in their article published in 1988. The authors state, that:

> "[...] despite the dozens of tactile sensor designs that exist, it is becoming clear to researchers that much work remains to be done at the system level before machine touch can be understood and then used in dynamic manipulation processes."

Until today only very few examples of successful integration of tactile sensor into robotic fingertips have been reported, e.g. Weiss et al. [177].

The literature review presented in chapter 2 shows, that for each and every requirement tactile sensors have been presented fulfilling that selected requirements. Review articles, e.g. by Argall and Billard [4] or Dahiya et al. [20] show, that the individual challenges can be met, however not all at the same time:

- High sensitivity, e.g. Mannsfeld et al. [94]
- High spatial resolution, e.g. Kolesar and Dyson [69]
- Robust sensor design, e.g. Fritzsche et al. [35]
- Integration into a robotic system, e.g. Weiss and Wörn [177]

When the combination of the ideal properties is considered, conflicts of goals arise. Even if the challenge of the spatial and functional integration of tactile sensors into a robotic system can be solved, to the best knowledge of the author, no tactile sensor system exists that is able to meet all requirements at the same time. Especially, the conflict of goals between the desired high sensitivity and a collision tolerant design that is required for real world application of tactile sensors on a robotic system remains unsolved. In addition, the results from the development of tactile sensors for robotic fingertips can often not directly be scaled to meet the requirements of whole-body touch sensitive covers for humanoid robotic systems. Especially, the underlying materials and processing technology in most cases can not be scaled. Figure 1.6 depicts a summary of the implications of the operation of tactile sensors on a robotic system. The physical interaction between the robotic system and its environment can be classified according to in which scenario the physical interaction occurs. Depending on the scenario different characteristics of the artificial skin with respect to sensing capabilities and mechanical properties are required. Physical interaction between the human user and the robotic system requires a high sensitivity and an intuitive operation but is less demanding with respect to transduction quality, as the human user is capable to adapt to the transduction characteristics. For robotic manipulation of objects the detection of multiple simultaneous contact events is mandatory as well as the acquisition of the interaction

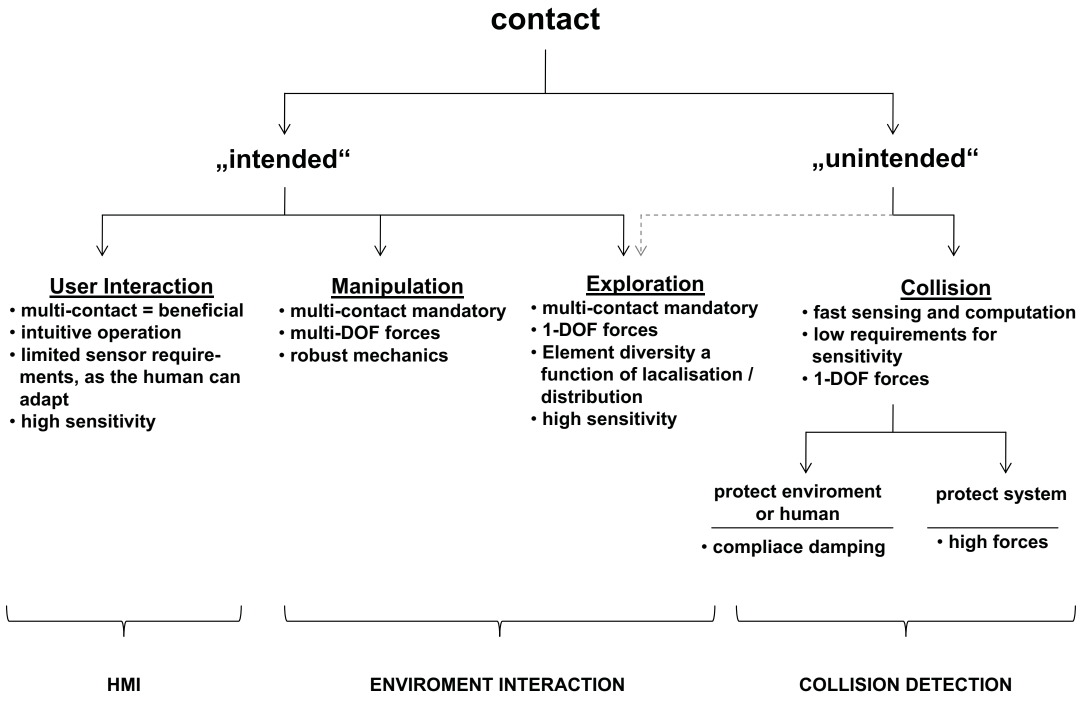


Figure 1.6: The general contact event can be classified according to, wether the contact between the robotic system and the environment or the human user is intended or unintended.

forces is multiple degrees of freedom. In addition, manipulation tasks require a robust sensor setup, as constant wear and tear challenge the tactile sensor during manipulation tasks. Robotic exploration tasks demand a high sensitivity and the reliable detection of multiple contacts whereas do not necessarily require multi DOF acquisition of the interaction forces. Finally, the detection of unintended collisions during the physical interaction requires fast sensing and pre-processing in order to enable the initiation of adequate collision reaction strategies.

1.3 Contribution of this thesis

Within this thesis the development of tactile sensors is extended towards the design of a multi-functional artificial skin for robotic systems. Therefore, an operation-oriented approach is pursued that takes into account the requirements that arise from the operation on a robotic system in real world application. While enabling a high initial sensitivity that allows for the detection of indentation forces as small as $0.05\ N$, collision forces that exceed $50\ N$ can be exerted on the sensor without mechanical damage. Based on general design paradigms that enable the solution of the conflicts of goals, an overall concept for the design of a stretchable artificial skin for robotic systems is proposed. The concept is based on the design of compatible functional components that can be parameterized individually and enable the integration of additional sensory or mechanical functionality without introducing new conflicts of goals. The individual adjustable functional components are designed to contribute to the desired overall properties of the resulting artificial skin. Based on the adaptive combination of the functional components a multi-functional artificial skin is created that can be tuned to the requirements of the individual application site e.g. on a humanoid robotic system. To facilitate the future integration into a robotic system the resulting artificial skin can be scaled with respect to sensor surface area, spatial resolution, and transduction properties. Therefore, an integrative approach for the design of the artificial skin and the required scalable polymer manufacturing processes is pursued. The scalability of the sensor design is based on the development of scalable manufacturing processes and the required polymer materials. Material science herein is understood as a tool rather than as a purpose in itself. For the implementation of stretchable tactile surface sensors able to cover the 3D curved surfaces of modern robotic systems, electrically conductive elastic polymer compounds are developed. In order to demonstrate the effectiveness of the proposed design paradigms a tactile surface sensor prototype is implemented that combines high initial sensitivity with the required robustness for the operation in real world robotic systems. In addition, a standard test procedure for the evaluation of tactile sensor systems is proposed in order to enable the comparison of tactile sensor systems developed all over the world. To encourage the introduction of the proposed procedure a set of simplified tests based on cost effective equipment is proposed.

Within this thesis an overall concept for an artificial skin that takes into account a future integration into a robotic system is proposed. Therefore an extended set of concepts for functional components with additional functionality with respect to the acquisition of shear forces and slip detection as well as thermal conditioning functionality of the artificial skin is derived. The artificial skin hardware developed in this thesis is focussed on a tactile surface sensor that is capable to transduce the most prominent mechanical modalities of the indenting stimulus. The prototypical implementation of the entire set of functional components, e.g. thermoregulation and temperature acquisition will be subject to future studies. Similarly, the implementation of higher level readout strategies, e.g. for the distal computing of the detection of edges will not be addressed within this thesis.

1.4 Outline

This thesis consist of five chapters, following the above introduction to the field of tactile sensing in robotic systems the literature describing the related state of the art in science and technology is reviewed in chapter 2. The literature research reveals that currently no general approach towards an adaptable artificial skin for robotic systems exists. Therefore in chapter 3 an overall concept for a multi functional artificial skin is derived. The development and the structure is based on the design methodology for mechatronics systems proposed in VDI 2206 [169]. The procedure is adapted for the design of an artificial skin. Consequently, a design approach based on an integrative design of the functional components the required manufacturing processes is pursued. For this thesis this approach is extended to materials research for the derivation of the required material properties of the sensor hardware. In chapter 4 a standard test procedure for tactile sensor systems is proposed and applied for the evaluation of the properties of the generated prototypes. In addition, a set of experiments demonstrating the successful integration of a tactile surface sensor into an existing robotic system is presented. In the final chapter 5 the results and findings of this thesis are summarized and future work is outlined.

2

State of the Art

A possible reason that there are no commercially available touch sensitive covers for robotic systems may be the complex shape of the covering structure of modern robotic systems. Especially, humanoid robotic systems are designed to mimic the shape of a human body in order to increase the acceptance of the robotic systems by the human user, e.g. see the study of the so called uncanny valley of Mori [96] or MacDorman [93]. To resemble the shape of a human body, the covering structure of humanoid robots has to be based on complex organic volumes with 3D-curved surfaces that can no longer be formed by the combination of simple cuboid or cylindrical volumes. These biologically-inspired surfaces are mostly non-developable and can not be covered with a single tactile sensor based on a rigid or one-dimensionally bendable circuit board. The progress of the state of the art artificial tactile sensing for robotic systems has been documented over the last thirty years in various review articles, [50, 103, 54, 86, 8, 85, 29, 162, 146, 20, 188]. The majority of the tactile sensor prototypes presented in literature has been based on planar printed circuit boards (PCB). Based on this technology simple geometric forms as cubes can be equipped with tactile sensors, see figure 2.1(a). Recently, an increasing number of tactile sensor prototypes based on bendable PCBs also referred to as flexible PCBs are capable to cover one-dimensionally curved surfaces, see figure 2.1(b), e.g. cylinders or cones. While there are various examples of tactile

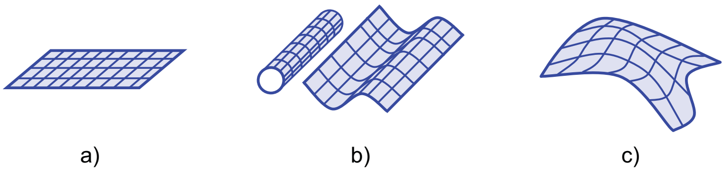


Figure 2.1: Planar surfaces, a) can be covered with tactile sensors based on rigid printed circuit boards, one-dimensionally curved surfaces b), e.g. cylinders can be covered with bendable tactile sensors based on flexible polymer based circuit boards, 3D-curved surfaces c) can not be directly covered with tactile sensors based on standard printed circuit boards

sensors on the cylindrical shapes of robotic manipulators, e.g. Wösch and Feiten [183] or Kerpa et al. [65], there are only a few approaches towards sensor setups which are able to cover the arbitrary 3D-curved outer surfaces of today's humanoid robots, see figure 2.1(c). Two basic approaches to cover 3D-curved robotic surfaces are pursued. Figure 2.2 depicts the two basic approaches. The first approach, depicted in figure 2.2(b), is to subdivide the 3D-curved surface, e.g. figure 2.2(a), into subsurfaces that can be covered with a rigid or bendable sensor module. The sensor modules are then combined to form a sensitive cover of the 3D-curved surface. The second approach, depicted in figure 2.2(c) is to cover the 3D-curved surface with a stretchable sensor. The extensibility of the sensor allows to directly cover concave surfaces even if the surfaces are non-developable.

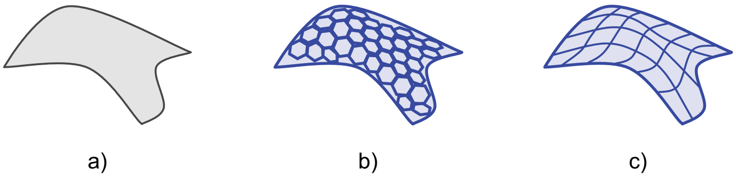


Figure 2.2: 3D-curved surface a) covered with a: Modularized tactile sensor b), stretchable tactile sensor c)

2.1 Modular tactile sensor systems

The application of a combination of tactile sensor modules allows to cover 3D-curved surfaces. The reduction of the size of the individual sensor module allows to cover moderately curved surfaces with rigid or bendable tactile sensor modules without affecting the resemblance of the shape of e.g. a humanoid robot too much.

Below a set of recent approaches towards modularized tactile sensors is presented in order of increasing ability to cover highly curved 3D surfaces.
Schürmann et al. [139] present a high speed tactile sensing module based on the measurement of electrical resistivity in conductive foam. The presented technology is based on the results of the work of Weiß and Wörn [177]. The sensor module consists of a rigid rectangular PCB that contains the contacting electrodes and readout circuitry. To form a sensor module the electrodes on top of the PCB are covered with a conductive foam. An indentation of the foam surface results in a change of electrical resistivity between the underlying contacting electrodes. The presented prototype provides 16×16 discrete transduction elements. In the style of the spatially distributed transduction elements in cameras ("pixel"), the transduction elements of spatially distributed tactile sensors are often referred to as "taxels". The sensitive area measures $8cm \times 8cm$. According to the authors the resulting spatial resolution of $5mm$ in combination with the sensor surface suffices for the detection of objects like a cup or glass. For the evaluation of the material properties of the foam cover the authors compare a $6mm$ thick sample of an unspecified carbonized Polyurethane (PU) based foam and a $5mm$ thick foam sample extracted from the commercially available DSAMOD sensor system of Weiss Robotics [66]. The authors state, that the PU based foam enables a higher initial sensitivity but saturates at a lower force level than the DSAMOD foam. The given initial sensitivity of $1\frac{g}{mm^2}$ is sufficient for robotic exploration tasks. The saturation at $3\frac{g}{mm^2}$ results in a quasi binary sensor behavior if the entire range of expected interaction forces (typical maximum fingertip force of a robotic hand: $30N$, e.g. Butterfass et al. [11]) is considered. According to the authors the presented prototype might be the basis for the development of a 1-dimensionally bendable sensor comparable to the sensor prototype presented by Kerpa et al. [65].
Mittendorfer and Cheng [98] propose a modular multimodal sensing system that allows for the acquisition of different modalities of an external stimulus. The presented sensor system is applied on a light weight robotic manipulator. According to the authors the sensor system consists of off-the-shelf accelerometers, temperature and proximity sensors. For the modules rigid PCBs are chosen for cost and reliability reasons. The introduction of flexible or stretchable connecting wires is planned in order to enhance the ability of the sensor system to conform to 3D-curved surfaces. The authors state, that in principal the size of the sensor modules could be scaled down, but for the presented prototype the scaling is limited by the size of the applied micro controller. The authors expect the interconnects between the individual modules to fail during rough physical interaction. Therefore the routing of the connecting wires is redundant, where only one of the applied four connectors

needs to be functional to ensure the operation of a sensor module in the network. As the sensor system currently does not provide pressure sensing capabilities, direct tactile sensing is simulated by the applied proximity sensors. The temperature sensing exploits the enhanced temperature of the sensor system that is mounted on an operating light weight robot in order to enable the acquisition of thermal energy dissipation if thermally conductive objects are in contact with the sensor. Mittendorfer and Cheng [98] state, that the experiments regarding the thermal sensitivity are conducted without polymer cover.

Cannata et al. propose a modular tactile sensor system based on the acquisition of capacitance changes. The individual modules have a triangular shape inspired by computer graphics. According to the authors the applied triangles enable the covering of 3D-curved surfaces of a humanoid robot. Each sensor module consists of a bendable triangular PCB that provides the electrodes of the capacitors on one side and the wiring and off-the-shelf capacitance to digital converters. The PCBs are covered with a $3mm$ to $5mm$ thick layer of silicone rubber to provide a compliant surface. To enable the acquisition of changes in capacitance the sensor modules requires a reference electrode. The sensor modules can be operated in two different configurations. First, the sensor is operated without a fixed reference electrode. This configuration utilizes the indenting object as reference electrode. Consequently this configuration is limited to the detection of conductive objects, e.g. human fingertips. In the second configuration a conductive cover is applied on top of the silicone rubber. This conductive layer then acts as reference electrode. Thus, an indentation caused by the contact of a non-conductive object results in a displacement of the covering conductive layer. Due to the deformation of the silicone layer the distance between the electrodes is altered. The resulting change of the capacitance is acquired by an off-the-shelf transduction chip. A single module of the presented prototype provides 12 electrodes enabling a spatial resolution of about $5mm$. The authors state, that the readout frequency for each module is $50Hz$ and can be increased up to $500Hz$ if all electrodes of one module are combined to gather an average measurement. The combination of modularization with the application of bendable sensor modules allows to cover the 3D-surfaces of a small humanoid robot. For the application on highly curved structures, e.g. the robot fingertips specialized segments are applied, e.g. Schmitz et al. [133].

Fritzsche et al. [35] introduce a textile based tactile sensor that is capable of covering moderately curved 3D-surfaces. The sensor is based on the measurement of the pressure induced changes of the resistivity of a polymer foam between textile conductive pathways that are arranged in a matrix setup.According to the authors the resulting sensor layer is approximately $2mm$ thick and can be operated on top of a $20mm$ thick energy absorbing layer referred to as cushioning layer. This layer provides passive safety enhancement in robotic application. The authors state, that the applied analog to digital converter (ADC) operates at up to $20kHz$ and enables a resolution of $10bit$. The textile material allows for the development of specialized sensory covers for robots that can literally be tailored to fit the outer shape of target systems. The authors claim, that the sensor concept can be modified to suit the requirements regarding shape, size and number of sensor cells. According to Fritzsche and Elkmann [34] the presented matrix controller allows for the evaluation of sensors consisting of up to 32×32 sensor cells. The authors state that the size of the sensor cells can be scaled between $5mm \times 5mm$ and $75mm \times 75mm$ per sensor cell. The scaling of the size is limited by the applied material that jackets the chambers of the individual sensor cells. Thus, the presented approach is not suitable for applications where high spatial resolution is required, e.g. the fingertips of a robot hand.

Lee et al. [84] present a flexible modular tactile sensor based on the measurement of changes in electrical capacitance. The sensor modules consist of an array of capacitors embedded into a flexible polymer matrix. The individual taxels are connected via $0.02mm$ thick electroplated copper electrodes. A single sensor module is $22mm \times 22mm$ equipped with 16×16 taxels with a spatial resolution of $1mm$. According to the authors the maximum frame rate for 16×16 taxels is $1kHz$. The size of the sensitive area can be enlarged be combining multiple sensor modules. The individual sensor modules are connected with a conductive adhesive that, according to the authors, can not be separated without the destruction of the sensor modules. While enabling a reliable operation under mechanical loading an adhesive based connection of the individual modules prevents an easy exchange of non-functional sensor modules.

As a conclusion, the modularization of the surface of the robotic system allows to cover moderately curved 3D surfaces with rigid or bendable tactile sensors that can be manufactured based on well established processes that are applied for the design of printed circuit boards. For surfaces with a high curvature the size of the individual sensor modules has to be minimized. Accordingly, the number of often mechanically fragile electrical interconnects between the individual sensor modules will increase. While the application of standardized manufacturing technology simplifies the design of the sensor modules, the applied rigid or flexible materials prevent the covering of the highly curved surfaces and thus the successful integration of modular tactile sensors towards a whole-body cover for modern robotic systems. Furthermore, faceted surfaces may be functional, but represent only an approximation of the intended design.

An alternative approach towards a touch sensitive cover for robotic systems is the application of polymer based tactile sensors that allow for a reversible elastic deformation and thus enable the covering of non-developable 3D curved surfaces of a robotic system. Below the current state of tactile sensors based on stretchable setups is outlined.

2.2 Stretchable tactile sensor systems

Today, an increasing number of research groups targets the development of stretchable electronic circuitry amongst others for the application in tactile sensors. The review on dexterous in-hand manipulation by Yousef et al. [188] provides an overview of the development of stretchable sensors. In general there are two basic approaches for the design of stretchable circuit paths for the design of stretchable tactile sensors. The most common is the application of metal based circuit tracks that are manufactured in a shape that allows for an elastic extensibility. The second approach is based on the development of dedicated polymer based electrically conductive materials that are then applied for the design of stretchable tactile sensors.

Cheng et al. [16] present a twistable tactile sensor prototype based on the measurement of changes in electrical conductivity in a conductive polymer. The taxels are arranged in an array setup. Each taxel consists of a small volume of conductive polymer that is connected on top and bottom by spiral electrodes. The manufacturing of the electrodes is based on a winding process. According to the authors, the desired partial extensibility of the connecting wires is enabled by a copper filament with a diameter of $0.25mm$ that is wound in a spiral around an elastic, non-conductive polymer filament with a diameter of $0.3mm$. The authors state, that the presented prototype can be applied on the arbitrary surface of a human shaped lower arm. The integration of the hard-soft interface between metal electrode and polymer based taxel into the mechanically loaded sensing area creates a limitation to the mechanical robustness of the tactile sensor. Moreover, the mechanical connection between the conductive polymer that is applied at the crossing points of the spiral electrodes, conductive graphite is utilized to enable the electrical connection to the "conductive polymer bumps" punched from the ready cured conductive PDMS compound. Therefore there are two interfaces: First the interface between the copper wire of the spiral electrode and the conductive graphite adhesive; secondly the interface between the conductive graphite and the conductive PDMS compound. Although the presented sensor prototype is stretchable enough to be wrapped around a ping pong ball the major limitation of this approach is the orientation and geometric fixation of the spiral electrodes during the manual assembly process.

The works of Lacour and Wagner, e.g. [75, 172, 76, 17] represent the fusion of the application of metal conductive structures and the utilization of polymer substrate. The authors present electrically conductive circuit tracks based on thin films of gold ($< 100nm$) that are deposited onto a pre-strained polymer substrate. After the deposition of the thin gold layer the basic substrate is released resulting the substrate to contract based on the elastic restoration forces. This contraction results in a wavy electrically conductive structure. According to the authors the resulting circuit tracks can be elongated up to 1% without a significant increase in electrical resistivity. A further stretching of the gold plated polymer substrate results in a linear increase of the electrical resistivity up to a strain level that ranges between 10% and 20%. Further stretching results in a fast increase of the measurable electrical resistivity. The applied electron beam evaporation requires a vacuum chamber, thus the maximum size of elastic circuits that can be manufactured at a time is limited by the size of the vacuum chamber. Therefore the pursued approach is not scalable to the manufacturing of large area stretchable circuits as required e.g. for the manufacturing of tactile sensors for the torso of a humanoid robotic system.

Gonzales, Vanfleteren and colleagues, e.g. [42, 43] present a stretchable electronic circuit based on planar meandering copper based circuit tracks. According to the authors the proposed meandering structure allows for an overall elongation of about 25% before the copper based circuit tracks mechanically fail. The applied spin-coating of the photo-resist for the etching process prevents the scaling of the process for the manufacturing of large area tactile sensors.

A similar approach is pursued by Lin and Jain [90] who propose a double layer design for metal based interconnects based on a meandering structure of the circuit tracks. According to the authors a maximum strain of the interconnects of over 50% is possible yielding a maximum change in electrical resistivity of 5%. While the authors claim to employ a scalable manufacturing process, again, the employed eximer laser ablation process as well as the spin-coating process limit the maximum size of tactile sensors that can be manufactured applying the presented manufacturing processes.

Amongst the most sophisticated approaches towards stretchable electronic circuits is the work of Rogers and colleagues, e.g. [67], who present a technology that allows for the generation of stretchable and foldable silicon integrated circuits. Multiple conductive and semi-conductive layers are deposited on a polymeric substrate. The silicone is strained before the integrated circuits are transferred to the silicone substrate in order to create stretchable CMOS circuits. Thus, enabling stretchable integrated circuits that can be elongated up to 10% and wrapped around a microscope glass slide cover with a thickness of $100\mu m$. The applied manufacturing principles require extremely sophisticated and costly manufacturing and processing equipment but enable the design of impressively deformable electronic circuits.

A different approach towards stretchable tactile sensors is pursued by the following research groups. Instead of applying metal based conductive structures onto polymer based substrates the research is targeted towards the design of polymer based conductive materials that enable the design of stretchable polymer based tactile sensors. The major challenge is the solution of the conflict of goals between the desired high electrical conductivity and the required stretchability. Furthermore, it is necessary to decrease the strain dependency of electrical resistivity of the polymer based circuit tracks in order to enable the reliable operation of the resulting electronic circuits under mechanical strain. The approach presented by Shimojo et al. [145] enables a tactile sensor hardware that can be fit arbitrary surfaces. The individual sensory elements are based on resistive rubber that is arranged in a net structure. The small number of four readout wires is independent of the sensor area and enables a fast response time of about one millisecond. The most prominent limitation of this approach is low spatial resolution of $10mm \times 10mm$ per sensing element as well as a lack of scalability of the sensor surface area.

Alirezaei et al. [2] present a stretchable fabric sensor that is capable of covering arbitrary 3D surfaces, e.g. the face of a mannequin. The tactile sensor is based on a so called tomography principle that allows for the reduction of the required readout wires. The presented prototype requires readout wires only at the rim of the tactile sensor. Based on the analysis of the electrical conductivity of a net structured conductive fabric between the individual contacting electrodes at the rim of the sensor the location of a mechanical indentation can be computed applying a strategy that is similar to tomography. The presented approach is limited with respect to spatial resolution as well as the detection of multiple simultaneous indentations.

Noda et al. [107] present a stretchable tactile sensor for the joints of robotic systems. The acquisition of changes in strain is based on ionic liquid in channels that are embedded in silicone. The stretching of the sensor results in a change of electrical resistivity that can be acquired from copper based electrodes that contact the ionic liquid. A surface structuring (silicone bump) on one of the two parallel channels is applied as detection point for indentation forces on the curved surface. The major limitation of the presented approach is that it requires a separate channel for each individual taxel plus one channel for the measurement and compensation of the stretch induced by the movement of the joint of the robotic system.

Amongst the most sophisticated approaches towards electrically conductive polymer based circuit tracks is the work of Someya and colleagues, e.g. [152, 152, 142]. The presented stretchable organic light emitting diode (OLED) matrix display presented by Sekitani et al. [142] is based on individual pixels that are connected by polymer based circuit tracks. The tracks are manufactured from a polymer that is filled with carbon nano tubes (CNT). The resulting material exhibits a high electrical conductivity and, even more impressing, shows almost no strain dependency of the electrical resistivity up to mechanical strains of over 100%. In addition, the conductivity of the materials is reversible if stretched up to 100%. The uniform dispersion of the CNT requires a very sophisticated chemical processing of the individual ingredients. The only drawback of the presented approach with respect to the application of the resulting sensors is the integration of mechanically rigid elements, e.g. transistors. This prevents the design of a mechanically overload proof tactile sensor for robotic systems.

The majority of the stretchable tactile sensor prototypes that have been presented in section 2.2 is manufactured applying manual manufacturing procedures (e.g. Yang et al. [187], who manually place individual electrodes for each taxel of a 32×32 tactile sensor matrix). While the manufacturing of a prototype will always involve manual processing, the applied procedures and processes have to enable a later automation of the manufacturing process as well as the spatial scalability of the sensor manufacturing for whole body cover of a humanoid robotic system. For the manufacturing of polymer based stretchable tactile sensors no dedicated manufacturing technologies are available. Therefore many stretchable tactile sensor prototypes are based on processes derived from the manufacturing of polymer based electronic components, e.g. OLED. These processes often apply silicon wafers and etching processes that are known from the manufacturing of micro electromechanical systems (MEMS). The size of the applied silicon wafers limits the maximum size of the resulting tactile sensors, e.g. spin coating of thin polymer foils onto a silicon wafer, e.g. [82, 152, 13]. The application of standard polymer processing machinery, e.g. extrusion, calandering and injection molding for functional polymer products is not easily scalable to the small size and minimal material volumes that are required for the manufacturing of tactile sensors for robotic systems. In addition, the applied processes have to allow for the manufacturing of tactile sensor that are capable to cover 3D curved surfaces. While a stretchable design poses many additional challenges, e.g. manufacturing and robustness, it offers a plenitude of opportunities for the design and implementation of tactile surface sensors. To the best knowledge of the author no tactile sensor design exists that is based on a scalable polymer processing technology that enables the automated manufacturing of stretchable tactile sensors for the highly curved surfaces of robotic fingers and at the same time allows for the processing of large area tactile sensors for a whole-body cover of the 3D curved surfaces of robotic systems.

2.3 Discussion

Already in 1988 Jacobsen et al. [57] stated:

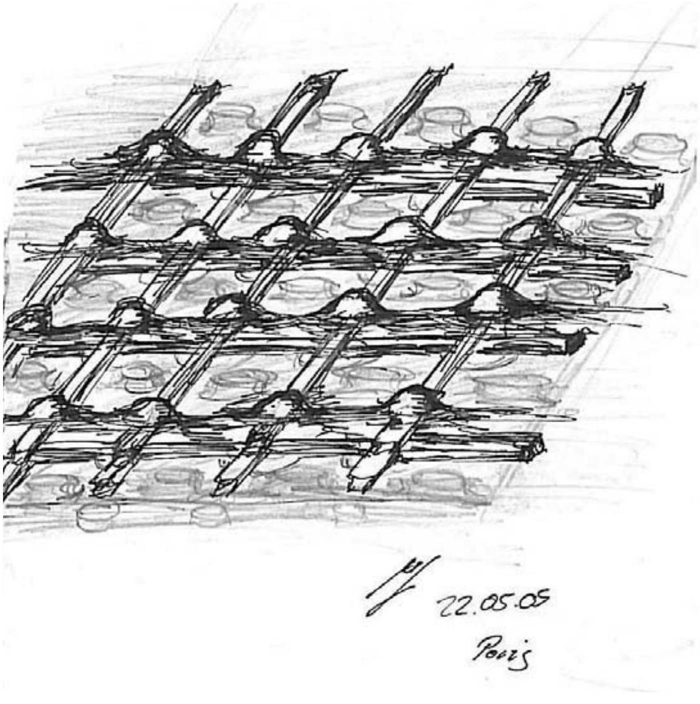
> "If an ideal tactile sensing system satisfying [the] desired performance criteria could easily be built, it would already have been done, and researchers would now be focusing in earnest on the deeper issues of how tactile data should be used in active machine manipulation. Unfortunately, only partial systems exist, often consisting only of cleverly designed transducer arrays with little potential for immediate application in research because of their low reliability, lack of interfacing hardware, or bulky geometry."

Unfortunately, today – almost a quarter of a century later – the same holds true for the research efforts towards tactile sensor systems. The analysis of the state of the art artificial tactile sensing shows, that even today the majority of tactile sensors is developed with a focus on the transduction properties of the sensors. Although the research towards artificial tactile sensing for robotic systems has a long history, even basic challenges regarding the mechanical properties of the sensors and especially the unification of the required robustness and high sensitivity are still to be solved. Moreover, the presented tactile sensor prototypes are mostly specialized for a very specific task e.g. the acquisition of the pressure distribution on the robotic fingertips. While an increasing number of research groups has shifted the focus from the development of transduction hardware towards the development of tactile sensor systems, the applied materials and design approaches for the tactile sensor hardware are in most cases still not capable of fulfilling the basic requirements of high sensitivity and compliance of the sensor surface. Although the systems orientation seems to be promising with respect to the generation of de facto integrable tactile sensor systems the majority of the presented tactile sensor systems are prototypes showing that there is still a long way to go until robots can be fully covered with a touch sensitive layer. One of the major challenges on this way is the development of manufacturing technology that allows for the automated processing of tactile sensors with very high spatial resolution for the application on robotic fingertips as well as large area tactile sensors that enable a whole body touch sensitive cover for humanoid robotic systems.

Instead of targeting the research efforts towards a new transduction principle the approach pursued within this thesis focuses on the development of an implementable sensor design that exploits well investigated transduction principles for the sensing capabilities. One may conclude from the analysis of the state of the art, that in order to achieve the desired combination of high sensitivity and overload-proof, collision tolerant design it is necessary to widen the scope from the development of tactile sensor systems towards a multi-functional artificial skin that can be scaled and adapted to the requirements of the application site on the robotic system. Thus, a spatial and functional integration towards an whole-body touch sensitive cover for real world application of robotic systems may become feasible.

3

Artificial Skin for Robotic Systems



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Within this chapter a general concept for the design of a multi-functional artificial skin for robotic systems is developed. The goal is to propose a work flow for the design as well as a toolbox of scalable functional components for the development of specialized touch sensitive covers for the respective application site on the robotic system. Based on the design methodology for mechatronic systems proposed in VDI 2206 [169], see figure 3.1, an operation–oriented approach is pursued, that accounts for the requirements and constraints arising from the spatial and functional integration of an artificial skin into a robotic system.

Based on the partitioning of the functional range, adjustable functional components are developed during the domain specific design. The result is a toolbox of adjustable functional components with optimized functionality. The integrative design of the functional components and the required manufacturing processes accounts for the required scalability of sensor system and manufacturing processes. Based on the combination of the properties of the individual functional components the desired overall behavior of the artificial skin can be obtained. Thus, the adaptation of the properties of the artificial skin to the respective requirements of the different application sites on the robotic systems can be implemented. During the system integration, exemplarily a stretchable tactile surface sensor is developed and implemented based on the proposed manufacturing processes. The required materials are investigated in order to suit the developed manufacturing procedures and thus enable the implementation of the designed sensor setup.

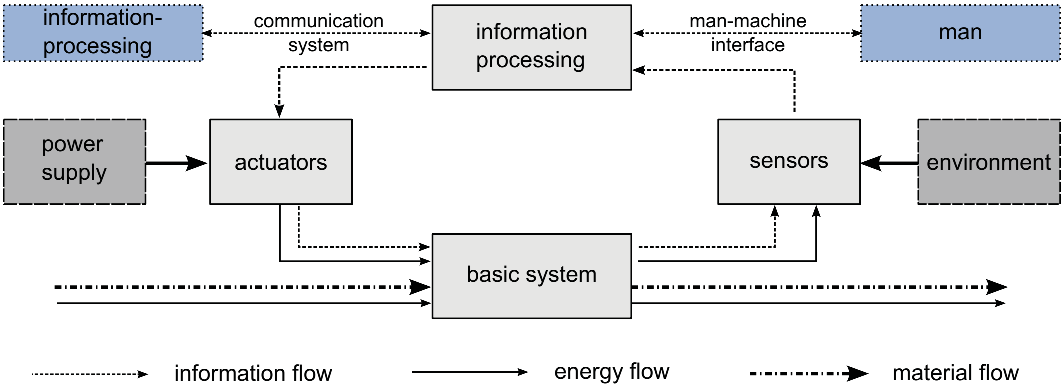


Figure 3.1: Mechatronic system components according to VDI2206 [169]

3.1 Methodology

The high spatial integration of mechatronic systems in general requires an optimal design of the individual components of the overall system. The design of an artificial skin system that enables a successful integration into a robotic system has to consider the constraints arising from the integration. Therefore, the system constraints for the later functional and spatial integration are crucial for the design process. According to VDI2206 [169] "Mechatronic systems comprise a basic system, sensors, actuators and information processing". The authors propose the representation of the relationship between these components as flows of material, energy and information. Additionally a concept for the modularization and hierarchization of complex mechatronic systems is proposed. Applied to the integration of artificial skin into the hierarchy of a robotic overall system the following flows between robotic system and covering artificial skin can be defined:

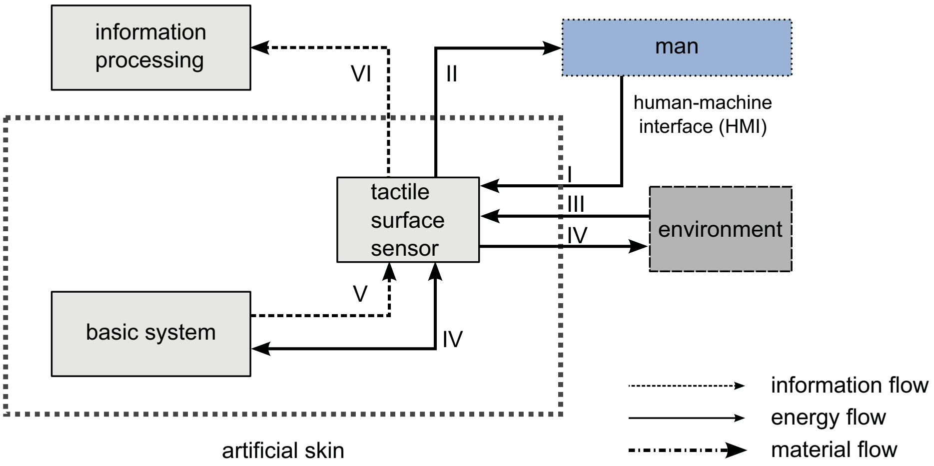


Figure 3.2: The introduction of an artificial skin results in the increase of the number of interfaces

Material flow between robot and skin is limited, examples could be fluids for adaptive control of the mechanical damping properties of the skin, or the supply of cooling agents from the robot to the skin sensor system.

Energy flow consists of mechanical energy, electric energy and thermal energy. The covering structure of the robotic system mechanically supports the artificial skin. In the case of physical interaction of the robotic system with its environment mechanical energy is exchanged between the mechanical structure of the robot and the covering artificial skin. In addition, electric energy for the power supply of the artificial skin and its readout system is transferred from the robotic system to the covering artificial skin. Furthermore, electrostatic effects must be considered. The operation of robotic systems results in the generation of waste heat that has to be dissipated. Therefore, thermal energy from the mechatronic components of the robot has to be transported to the artificial skin, if no internal cooling can be integrated. Depending on thermal conductivity and thermal capacity of the applied materials the artificial skin acts as a barrier for thermal energy dissipation from the robotic system. This results in a thermal insulation of the robotic system and may necessitate an internal cooling of the robotic system.

Information flow from the artificial skin to the control system of the robotic system and vice versa must be established. The information of the artificial skin can be utilized directly or indirectly. The direct integration of the output of the artificial skin occurs if the data acquired by the artificial skin is applied in the motion control system of the robotic system. A collision event, detected by the artificial skin results in the activation of pre-defined reaction strategies of the robotic system. In this case the artificial skin acts as an additional source of information e.g. for redundant safety systems. The indirect utilization of the artificial skin data occurs if the data from the artificial skin is utilized for sensor data fusion in order to generate additional information from the combination of data from various sensor systems. An example is the combination of the resulting external force vector derived from the intrinsic sensors of the robot with the information about contact location and contact area distribution derived from artificial skin sensors. The reverse propagation of information (from the robotic system to the readout system of the artificial skin) can be applied in order adapt the readout strategies of the artificial skin system to the current state of the robotic system.

Important for the mechatronic integration is the definition of the interfaces for the flows between the different components of the overall mechatronic system. Following the effects of the introduction of an artificial skin into a robotic system are summarized.

The introduced artificial skin covers the basic system and thus acts as a barrier between the basic system and the environment. Thus, the introduction of an artificial skin into a robotic system results in an increase of the number of interfaces (declared with roman numerals in figure 3.2). In fact, the artificial skin acts as an additional interface between the basic system and the environment. The artificial

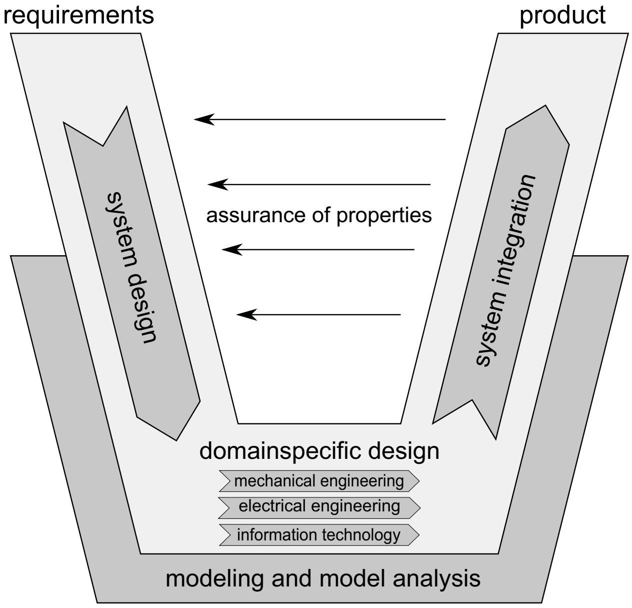


Figure 3.3: The V-model adapted for mechatronic systems design process, according to VDI2206 [169]

skin acts as an interface between the basic system and the environment. The intended physical interaction of the robotic system with the environment, e.g. during robotic manipulation of an object, mechanical energy is transmitted in both directions (I, IV) via the artificial skin surface. The tactile sensors of the artificial skin transduce the external mechanical stimulus into a measurable quantity and provide tactile information for the information processing unit of the robotic system, figure 3.2 (VI). In addition, the artificial skin acts as physical interface between the robotic system and human users. The tactile surface sensors of the artificial skin enable an additional channel for the intended pHRI, the artificial skin acts as a HMI, figure 3.2 (I). In order to enable an intuitive interaction for intended pHRI the sensitivity of the artificial skin has to be increased in order to minimize the required interaction forces that are required for the artificial skin to act as HMI. In case of an unintentional collision between the robotic system and the interacting human, mechanical energy is transferred from the mechanical structure of the robotic system (basic system), figure 3.2 (IV), via the covering tactile surface sensor to the interacting human, figure 3.2 (II). Based on the described flows and the identified interfaces between the robotic system and the environment a general concept for the design of an artificial skin is derived in section 3.2.7.

Following, the applied methodology for the design process is outlined. The structure of the design process is based on the design methodology for mechatronic systems presented in VDI 2206 [169]. According to the authors the adapted V-model can be applied as a methodology for the macro cycle of the design of mechatronic systems, it consists of the following steps:

- Identification of the requirements
- System design
- Domain-specific design
- System integration
- Assurance of properties

These steps can be accompanied by a supporting modeling and model analysis. A set of subsequent macro-cycles is required in order to advance the development from laboratory specimen over functional specimen to a mechatronic product that is fit for mass production. This structure is intended for product development in an industrial environment and thus is not directly applicable in a research environment. Therefore, the structure is adapted as follows. For this thesis, the structure of the V-model, see figure 3.3 proposed in VDI 2206 [169] is adapted for the research targeting the design of an artificial skin for robotic systems.

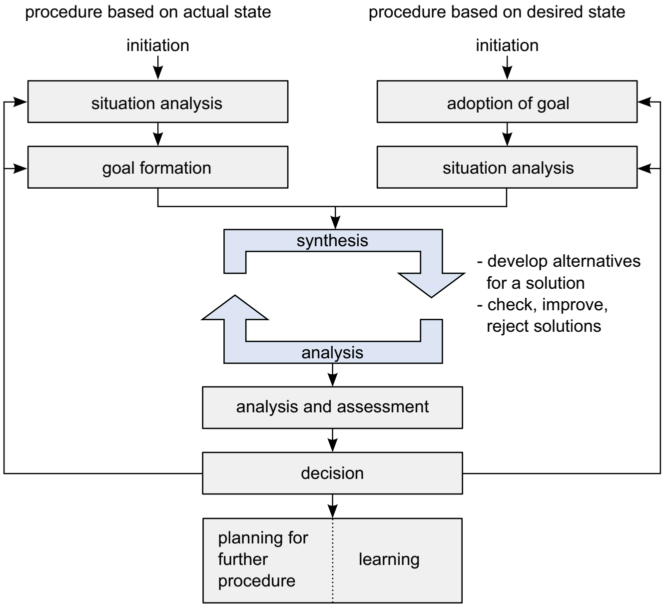


Figure 3.4: Problem solving cycle as micro cycle for the development of mechatronic systems, according to VDI2206 [169]

As no detailed development order is given for a research project the requirements for the desired tactile sensors system are based on the analysis of the current state in tactile sensing and the analysis of the requirements that arise from the spatial and functional integration of an artificial skin into a robotic system. Resulting from the analysis of the limitations of the current state of artificial tactile sensing for robotic systems the key challenges are identified.

During the system design a set of design paradigms for the design of the artificial skin for real world application is proposed, see section 3.2.7.

The domain-specific design is restricted to the design of solutions for the functional components of a tactile surface sensor hardware. Here the problem solving cycle presented in VDI2206 [169], see figure 3.4, is proposed for the derivation of solutions for the functional components of an artificial skin for robotic systems. Within the system integration exemplarily a tactile surface sensor is developed based on a selection of the functional components derived in section 3.4. Therefore, the functional components are combined to form a stretchable tactile surface sensor. Utilizing the proposed scalable manufacturing processes a set of tactile surface sensor prototypes is implemented.

3.2 System Design

The idea of applying results from the study of biological tactile sensing is all but new. The investigation of biological touch sensitive systems in order to derive approaches for the design of tactile sensors for robotic system has an equally long history as the development of tactile sensors itself. One of the first studies in this field is the work by Lederman and Pawluk published in 1993 in their chapter in [103]. Many of the bio-inspired approaches are based on a structure that is similar to the bionic approach presented in Neumann et al. [102]. Other bionic approaches are presented by Hill [53], Zerbst [189], Lindemann [91] and Stricker [154]. The underlying basic structure of these approaches mostly consists of the analysis of the technical challenge, the abstraction of the problem and a search for a solution for a comparable problem in biological systems. Following, the underlying structure, the principle or the strategy of the biological system is investigated and abstracted. Finally the abstract solution principle is transferred to a technically feasible solution of the problem. Applied for the development of artificial skin for robotic systems bio-inspired solutions are commonly derived from the analysis of human skin. For the design of artificial skin for robotic systems the sensory capabilities and physiological functionalities of human skin are the ultimate goal. The long term development of artificial skin sensors is aimed towards the generation of artificial skin that is able to provide a spectrum of functionalities as rich as human skin. In order to enable intermediate steps of the evolution of tactile sensors towards technical skin equivalents guidelines from human skin may be derived.

3.2.1 Human skin as design metaphor?

Experiments conducted by Monzee et. al [99] illustrate the loss of dexterity in humans if the thumb and the index finger of the human hand are anesthetized and the subject looses the sensory feedback from the fingertips. With respect to the outcome of the conducted experiments the authors state, that:

> "[...] the most striking effect shown by all subjects in this study was the use of vastly excessive grip forces during both lifting and holding [...]."
>
> "With cutaneous sensation intact, all subjects in the present study generated only very small forces in directions other than those intended for grasping and lifting. After digital anesthesia, the x- and z-axis linear forces arising from the force imbalance between the fingers and from pushing or pulling were significantly increased. In addition, significant

> off-axis torques appeared in the horizontal (y axis) and frontal (z axis) planes."

One may thus conclude, that the loss of tactile information from the fingertips results in a dramatic decrease in dexterity and that the mechanical properties of human fingertips without sensitivity are not sufficient for dexterous manipulation of small objects. On the other hand, the complicated handling of slippery objects demonstrates the importance of the mechanical interface between fingertip and manipulated object. Even the sophisticated sensory feedback from human fingertips is not always able to compensate for an insufficient mechanical contact between fingertip and slippery objects. Hence only the combination of sensory feedback and the mechanical composition of human skin result in the high dexterity observed in humans.

Composition of human skin

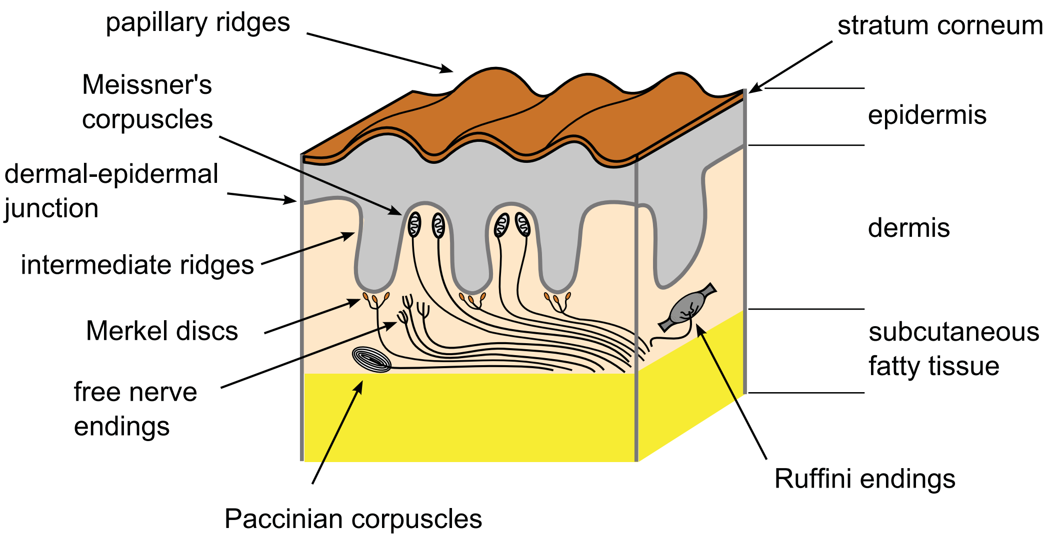


Figure 3.5: Human skin is composed of three main layers, the epidermis, the dermis and the subcutaneous fatty tissue; Figure adapted from Kandel et al. [64]

Figure 3.5 depicts the principal setup of the human skin. It consists of a set of layers with different mechanical properties. While the set of layer is identical over the whole body, a varying thickness of the individual layers results in different properties that are tuned to the requirements of the body site. According to Silbernagel and Despopoulos [148] human skin consists of three major layers, the subcutaneous fatty tissue, the dermis and the superficial epidermis. The subcutis consists of fatty tissue that is supported by connective tissue. The authors state, that human skin at the sole of foot consists of a thick layer of cutis which covers a pad of subcutaneous fatty tissue that is enclosed by pressure chambers formed by connective tissue. The setup of the pressure chambers results from the adaptation of the skin to the requirements posed by upright locomotion and the resulting high pressures that can occur on the sole of the human foot. This setup forms an anti-shock pad and in combination with a rich supply of blood vessels prevents decubital gangrene induced by high local pressure. According to McGlone and Reilly [97] the thickness of the dermis varies according to body site between $0.5mm$ at the eyelid and over $5mm$ in the non-hairy skin of the palm or sole of foot. The data related to the mechanical properties given in literature is highly variant and depends on the applied experimental method and data acquisition process. The direct in-vivo measurement of the mechanical properties of human skin is not possible as standardized tensile or compression tests on tensile testing machines are not feasible with living tissue. Therefore, various approaches towards the indirect measurement of the mechanical properties are presented in literature. A brief review of experimental methods for the determination is presented by Korthagen [70]. Hendriks [52] applies indentation, suction and torsion experiments for the derivation of the mechanical properties of human skin in vivo. The thickness of the individual layers of the skin on the human forearm is given according to Hendriks [52]. The so called stratum corneum exhibits a thickness between $10\ \mu m$ and $20\ \mu m$. The thickness of the living epidermis varies between $30\ \mu m$ and $130\ \mu m$. The thickness of the supporting dermis is approximately $1.1\ mm$ and the underlying subcutaneous fatty tissue $1.2\ mm$ thick. Many experiments for the derivation of the mechanical properties have been conducted applying dead tissue. According to Pailler-Mattei et al. [115] the mechanical properties of in vitro tested stratum corneum can be described by a Young's Modulus of about 1GPa. In vivo experiments with human skin are only possible on the surface of the intact skin. According to Diridollou et al. [25] the direct acquisition of the mechanical properties of the individual skin layers by vertical stress is not feasible. Therefore, computational models of the skin setup are applied to calculate the properties of the layers from the reaction of the entire skin. Hendriks [52] evaluates the deformation of human skin applying a suction device. An alternative approach is the modeling of human skin tissue, Gerling and Thomas [39] present a solid mechanics model for human skin layers. Dandkar et al. [21] propose a FEM model of the fingertip for the investigation of tactile sense and the underlying mechanics. The authors state, that a model consisting of multiple layers can approximate the behavior of human and monkey fingertips. Wu et

al. [184] propose a model of the human fingertip incorporating non-linear behavior of the tissue as well as effects of time-dependency. Tada et al. [161] present a model of the layers of subcutaneous tissue based on indentation test under MRI surveillance.
The majority of the presented computational models for the description of the mechanical properties of living human skin tissue is based on limited experimental data or applies simplifications for the description of the material behavior. Therefore, the presented computational models of human skin behavior are not suitable for the application in the design of artificial skin for robotic systems.

Sensory capabilities in human skin

Weddell and Miller [175] present an early review of the research towards the skin sensibility and outline the complexity of the research in this field. Järvilehto et al. [58] state that the functionality of cutaneous receptors in animals are similar to the one in humans. Their analysis also indicated a similarity of the receptors within glabrous and hairy skin. Johansson [60] investigates the sensibility in human skin and stated that there are four types of mechano-receptors with specialized functionality. In the same line of research Vallbo and Johansson [167] conduct experiments examining the two-point thresholds on the skin surface for the characterization of the size and distribution of the receptive fields of the human hand. They observed a reduction of spatial resolution from the fingertip (two-point threshold $1.6mm$) to the palm (two-point threshold $7.7mm$). Bruce and Sinclair [10] investigate the sensitivity threshold of the skin on the human finger. The authors propose a test setup that utilized the so called von Frey hairs, a set of mostly polymer based filaments that exhibit a defined force if pressed to the skin. If this defined force is exceeded the filament will bulge under the applied load and thus limit the transmitted indentation force. The authors extend the von Frey hair based manual test by fixing the von Frey hairs on an apparatus that enables the reproducible indentation movement of the hairs into the skin surface. The authors conclude, that the differences in sensitivity threshold do not correlate to the density distribution of the sensory cells but may result from difference in the propagation of the mechanical stimuli towards the sensory cells. Moreover, the authors suggest the significance of the density of free nerve endings to contribute to the sensitivity threshold. Goodwin et al. [44] analyze the effects of sinusoidal scanning movements of a grating over a monkey finger and state that the effect of changing scanning speed and grating properties are not independent. The influence of visual and tactile information on human dexterous manipulation of objects with varying shape has been analyzed by Jenmalm [59]. Edin [28] analyzes the sensitivity of human skin receptors under dynamic strain. Bell and Holmes [6] present a model of the dynamics of the receptor potential. In 1992 Johnson and Hsiao [63] present a review of the research targeting the neural mechanisms of tactual texture perception. The authors conclude, that pattern recognition is based on the activity of the SAI receptor system. Tangential forces exerted to human fingertips are evaluated by Birznieks et al. [9], they state, that single afferent nerve fibers are not able to decode the direction of tangential forces but from the combination of multiple afferent nerve fibers with their direction dependent sensitivity. The sensory capabilities of human skin are based on the data acquisition by a set of specialized sensory cells.

Sensory cells Human skin is equipped with a set of specialized sensory cells for the transduction of mechanical stimuli. The works of Johansson and colleagues, e.g. [60, 167, 62] have led to a generally accepted understanding of mechano-perception in human skin. In human glabrous, non-hairy skin four different sensory cell types, also referred to as low threshold mechano-receptors, have been identified. According to Westling and Johansson [179] the sensory cells or receptors can be categorized by the extension of the resulting receptive fields. Small (millimeter scale) sharply bordered receptive fields are grouped as Type I, larger (centimeter-scale) receptive fields with blurred borders are grouped as Type II receptors. In addition, a second classification is based on the behavior of the output of the receptors if the skin is statically deformed. The so called fast adapting (FA) receptors respond to changes in deformation and cease firing if the skin is statically deformed. In contrast to this, the so called slowly adapting (SA) receptors provide an output if the skin is statically deformed. The different types of sensory cells exhibit different transduction functionalities resulting in specialized transduction behavior The following sensory cells are distributed within human skin, Meissner's corpuscles, Merkel's disks, Pacinian corpuscles, and Ruffini endings, see figure 3.5. Ogawa [109] proposed the Merkel cells as mechano-receptors in the Merkel-Cell-Neurite (MCN) complex and thus can be considered as SA I receptors. According to Ogawa the MCN are located "at the basal layer of the rete-pegs" (ridges of the dermal-epidermal junction). Westling and Johansson [179] investigated the activity of mechano-receptors and state, that Pacinian corpuscles are highly sensitive to vibrations and amongst others participation in motor control. Until today there is no consensus regarding the exact transduction functionality of the individual sensory cells. Therefore, the knowledge of the sensory cells in human skin can not directly be applied for the design of the taxels of an artificial skin for robotic systems.

Receptive fields The surface areas on human skin that are enervated by a single afferent neuron are referred to as receptive fields. Depending on the type of sensory cell and its location within the skin layers the receptive fields vary in size and shape. Depending on the type of sensory cell the size of the receptive fields varies widely. According to Kis [68] the average diameters range from $2mm$ to $10mm$. The density of the sensory cells and thus the spatial extension of the receptive fields on the human hand have been investigated by Johansson and Vallbo [62]. Due to the mechanical filtering properties of the human skin layers the stimulus, e.g. of a point contact at the skin surface is laterally distributed. Thus, more than one sensory cell can be excited by the same stimulus which leads to so called overlapping receptive fields.

Conditioning of the stimulus The layers of human skin are not separated by planar layers but exhibit an undulating interface between the dermis and the epidermis, the so called dermal-epidermal junction, see figure 3.5. The widespread theory, that the intermediate ridges act as a set of levers that promote the input from the papillary ridges to the intermediate ridges originates from the analysis of photographs of cross section of the digital skin by Cauna [15]. Recent experiments and simulation contradict the lever theory and promote a theory that claims that the intermediate ridges rather bend than pivot and thus mechanically focus stress and strain at their tips where the Merkel cells are located [37]. Regardless of which theory holds true, it may be hypothesized, that the 3D shaped intermediate ridges support the mechanical conditioning of the external stimulus towards the location of the Merkel cells.

Signal preprocessing and transfer in human skin

Lederman and colleagues, e.g. [78, 80, 79] investigate the tactile sensing and processing mechanisms in biology, and propose approaches for the processing of tactile information derived from technical tactile sensors. An elaborate overview over human tactile sensing and perception with respect to the design of readout algorithms for tactile sensors is presented by Kis [68]. The author summarizes the findings from neuro-biology and outlines the implications for artificial tactile sensing. The signals from the sensory cells are propagated from the skin to the central nervous systems (CNS). The signal transfer happens in a parallel way, where the individual receptive field of the skin are enervated by parallel nerve fibers. This high grade of parallelization allows the transfer of large amounts of information from human skin to the central nervous system. A excellent description of the signal preprocessing and transfer in the human nervous system is presented by Kandel et al. [64]. The authors present the preprocessing functionality of the peripheral nervous system (PNS). Based on so called interneurons parallel nerve fibers interact during the transmission of the tactile information and enable the enhancement of the selectivity between two adjacent indentations on the skin surface. The signal preprocessing thus compensates for the loss of the spatial resolution that results from the mechanical properties of the layers of human skin. Kandel et al. [64] describe the signal preprocessing functionality of the PNS in humans. According to the authors the amount of tactile information, relayed form the PNS to the central nervous system is reduced by the application of adaptive neighboring gain self adjustment. If multiple neighboring channels relay a signal to the first synapse the individual signals influence the gain of the amplifier of the neighboring channels. Nature resolves this via the so called cross-inhibition based on interneurons. As no technical equivalent to the transmission and preprocessing of tactile information in human PNS is available the preprocessing of tactile information in artificial skin has to be based on conventional electronic circuits. The interested reader may be also referred to the extensive study of Johansson and Flanagan [61] who present a neurological analysis of human object manipulation based on tactile information. The authors conclude, that tactile information plays an important role for the acquisition of model parameters for the pre-task planning of a manipulation action.

Guidelines for the design of artificial skin

The review of the literature describing the capabilities of human skin reveals that especially the sensory capabilities are based on the entire perception system. The perception system includes the signal preprocessing in the PNS as well as the signal processing in the human brain. Thus, the tactile sensing functionality of human skin can not be considered independent of haptic perception or the cognitive abilities of the human brain. Especially, the model-based manipulation of known objects (e.g. the adjustment of the required arm stiffness and grasp force prior to the physical contact with the object) shows that human dexterity in manipulation results only in part from the sensory abilities. Therefore, for this thesis the sensory capabilities of human skin are regarded only as a source of inspiration for the design of the sensory elements of the artificial skin for robotic systems. Where appropriate, the underlying working principles are adapted for the system design of artificial tactile sensors and the development of the functional components. The combination of sensory functionality, preprocessing and the unique mechanical properties e.g. of the skin on human fingertips enables the dexterity and fine manipulation capabilities that are observed in humans. The functional range of human skin is based on the combination of a set of specialized functional components. The overall mechanical properties result from the combination of a set of specialized skin layers. The superficial stratum corneum acts as a protection layer that is constantly replaced to counter abrasion effects during everyday use. The underlying combination of epidermis and dermis contains the sensory cells. The mechanical setup and here especially the dermal-epidermal junction supposedly contributes to the transduction of external stimuli. The mechanical setup of human skin conditions the external stimuli to fit the sensitivity of the individual sensory cells. The subcutaneous fatty tissue in human skin exhibits mechanical damping and deformation properties and thus supports the cushioning of collisions and enables stable grasps that are required for human dexterity. Copying the mechanical properties of human skin would result in a viscoelastic, hysteresis-tending material behavior that is undesired for technical sensor systems. Following a bionic design approach the underlying principle of the functional partitioning of the capabilities is applied for the structuring of development process. The derivation of the artificial skin concept within this thesis is based on the functional partitioning observable in human skin.

3.2.2 Operation–oriented artificial skin design

Already in 1988 Jacobsen et al. [57] stated, that

> "A major portion of tactile sensing research has emphasized the fabrication of small, sensitive transducer arrays rather than the development of complete touch sensing systems. This emphasis has resulted in a large number of "bench top" sensors, very few of which have seen actual use in real manipulation systems."

The review of the current state in artificial tactile sensing reveals that little has changed in the last twenty five years. A possible reason for the small number of successfully integrated tactile sensor systems may be found in the pursued development approach. Many of the sensor prototypes presented in chapter 2 are motivated by material scientists seeking for a possibility to present the potential of the properties of newly developed materials. Therefore, new tactile sensor prototypes are created based on the developed materials. Many researchers consider the development of tactile sensor systems as a linear process, see figure 3.6. Based on the findings in material science sensor setups are designed that make use of the properties of the newly developed material. The transduction principle applied for the senor design is based on the constraints of the sensor design, which itself is dictated by the material properties. Thus, the design of the tactile sensors is triggered, and often constrained, by the properties of the materials. As a result of this approach, the resulting prototypes often contradict a later functional and spatial integration into a robotic system.

Following the linear development process the manufacturing technology is tailored to the properties of the developed material instead of focusing on the manufacturing process that is required for the implementation of an implementable tactile sensor setup. For the design of "classical" tactile sensor systems various approaches are presented in literature. The manufacturing processes of the sensor prototypes are often based on well established industrial processes, e.g. manufacturing of printed circuit boards or micro electromechanical systems (MEMS) based on silicon etching. The interested reader may be referred e.g. to the review of Dahiya et al. [20] as a starting point. The selection of the manufacturing process is mostly focussed on the manufacturing of a prototype. Very often, the manufacturing process is predetermined by the background of the respective research group. The applicability of the selected manufacturing processes for the implementation of large area (in the order of square meters, i.e. touch sensitive covers for entire robotic systems) is not taken into account. The focus on material science and the applied transduction properties overshadows the challenges of the later integration into a robotic system. Thus, the sequential development approach often results in laboratory prototypes that are not fit for the integration into an overall mechatronic system. The performance of these prototypes during the operation on a robotic system under real world conditions can in most cases not be specified.

Figure 3.6: The "classical" material science motivated approach towards an operation oriented approach, that takes into account the requirements of the operation of an artificial skin on a robotic system and accounts for the constraints resulting from the spatial and functional integration into a robotic system.

In order to overcome the limitations of the currently presented tactile sensor prototypes and further the successful integration into a robotic system the development process for the artificial skin within this thesis is reversed. In addition the cross correlation between the individual development steps is accounted for. Figure 3.7 depicts the dependencies of the development stages. For this thesis an operation–oriented development approach is pursued.

- Requirements for the operation on a robotic system
- Constraints from the spatial and functional integration into a robotic system
- Design of a scalable sensor system

- Design of the required manufacturing technology
- Materials research

Therefore, the development process is based on the analysis of the requirements for the successful operation of the artificial skin in real application scenarios on a robotic system. Subsequently, the constraints for the sensor data acquisition arising from the spatial integration are analyzed. The challenge of the sensor data acquisition and processing in artificial skin systems is exemplified for a robotic finger. Based on these requirements and constraints the scope of the derivation of a concept for an artificial skin is broadened from the sensory capabilities of "classical" tactile sensor systems to the multi-functionality observed in human skin. Aside from the sensing capabilities, the mechanical and thermal properties of the artificial skin are important to allow for a successful integration of the artificial skin into a robotic system. The derivation of the artificial skin concept accounts for the constraints stemming from the desired spatial and functional integration into a robotic system. The development of "classical" tactile sensor systems can be based on well established manufacturing processes, e.g. the design and manufacturing of standard flexible printed circuit boards. Due to the constraints from the integration into a robotic system and the requirements presented in section 2.2 the development of artificial skin sensors can not rely on such standard manufacturing processes. Therefore, specialized manufacturing processes have to be designed in order to enable the implementation of the proposed artificial skin setup. In order to apply the manufacturing processes specialized polymer materials have to be investigated. The requirements for the properties of the material are defined by design of the artificial skin and the applied transduction principle. In addition, the designed

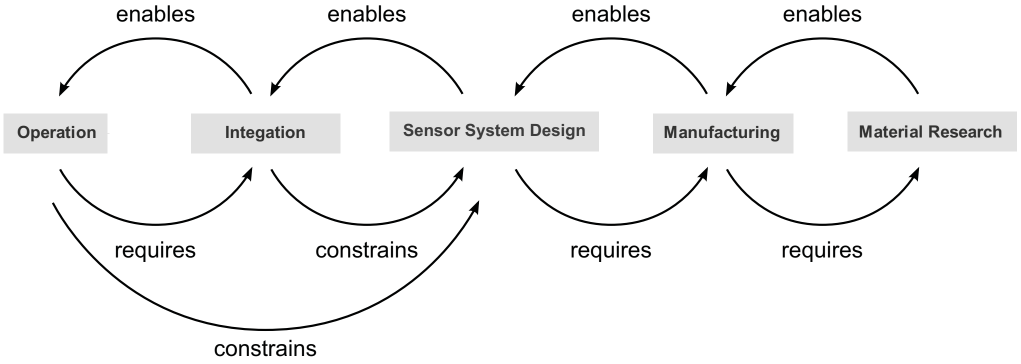


Figure 3.7: Operation–oriented development approach that takes into account the requirements of the operation of an artificial skin on a robotic system and accounts for the constraints resulting from the spatial and functional integration into a robotic system.

manufacturing processes require compatible properties of the material during the manufacturing, e.g. viscosity. Within this thesis material science is applied as a tool rather than regarded as a purpose in itself.

3.2.3 Integration into robotic systems

Prerequisite for the operation of an artificial skin on a robotic system is the successful integration of the mechanical structure of a robotic finger, figure 3.8(a) and a tactile sensor system, figure 3.8(b) and thus enable the implementation of an artificial skin, figure 3.8(c) for robotic systems. Based on the analysis of the current state of technology the following challenges have to be met in order to allow for a successful integration of an artificial skin into a robotic system:

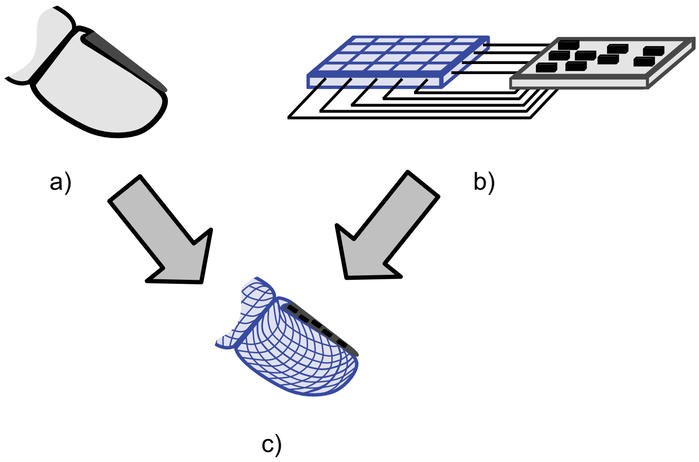


Figure 3.8: One of the key challenges on the way from tactile sensor prototypes towards an artificial skin is the spatial integration of a tactile sensing setup (b) into a robotic fingertip (a). In order to enable the successful integration the development of the artificial skin has to take into account the requirements and constraints arising for the desired spatial integration into a robotic system (c).

- Covering of non-developable surfaces
- Scalability of the artificial skin
- Scalability of the manufacturing processes

One of the most prominent challenges is the development of an artificial skin hardware that can be applied onto the 3D-curved non-developable surfaces of modern robotic systems. Two principle approaches are being investigated, the first based on the combination of rigid or bendable modules, the second based on stretchable materials. Various approaches towards the required covering of 3D-curved surfaces of modern robotic systems are outlined in chapter 2.

The second most prominent challenge is the size of the surface area of a robotic system. Ulmen and Cutkosky [166] state, that:

> "Though many sensors claim scalability, few sensorized coverings have actually been scaled to completely cover a robot, and to do so has required extremely simple sensor designs [...]."

Covering the entire surface of a robotic system poses the challenge of scalability of artificial skin sensors. Artificial skin sensor systems have to be adaptable to a large variety of possible application sites on structure of the robotic system. Ranging from the large area of the manipulator of a heavy duty industrial robot to the highly curved surfaces of a robotic fingertip.

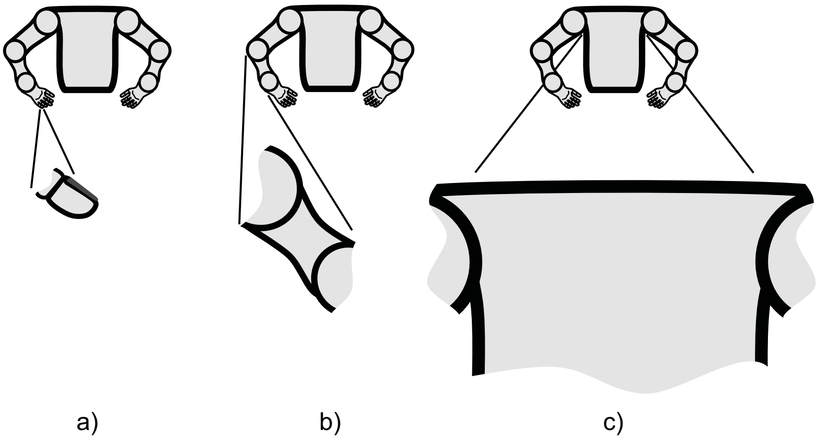


Figure 3.9: For a successful integration the size and shape of the artificial skin needs to be scalable in order to allow for the adaptation of the artificial skin according to the application site on the robotic system. While multiple approaches towards tactile sensor for fingertips are presented in literature (a), only few approaches towards the covering of a robotic arm structure (b) or even a whole-body sensitive cover for a humanoid robotic system are presented.

Scalable sensor surface area Many of the approaches presented in chapter 2 follow an approach for the development of touch sensitive covers for robotic systems that is based on the combination of identical sensor modules to cover the entire surface of a robotic system. The approach pursued by Cannata et al. [12] is based on identical segments that are applied to cover a humanoid torso and arms, while specialized sensor segments are designed for the fingertips. While enabling large area sensor systems this approach does not enable a site-dependent scaling of the surface area of the sensor segments. Scaling of the resulting sensor surface by the combination of identical sensor segments results in inflexibility with respect to sensor surface area as well as spatial resolution and contradicts the adaptation of the artificial skin to the requirements of the application site. True scalability allows for the adaptation of the sensor area of the individual segments to the site-dependent requirements, see figure 3.9. For each application site the size of the individual segments has to be adapted, e.g. for the fingertip of a robotic hand, figure 3.9(a), the forearm of a humanoid robotic system, figure 3.9(b), or for large area touch sensitive covers, e.g. for the torso of a humanoid robotic system, figure 3.9(c), Ohmura et al. [110] present a scalable tactile sensor principle that is based on the acquisition of reflected light that is introduced by a LED into a covering layer of urethane foam by photo-resistors. If the covering foam layer is compressed the amount of reflected light changes. These changes are measured by an adjacently applied photo-resistor. The major limitations of the proposed sensor system are the high energy consumption and the cumbersome manual application of the individual taxels onto the target geometry. In addition the scalability of the presented approach towards tactile sensors with a high spatial resolution is limited by the spatial low pass filtering of the applied urethane foam and the required wiring for the individual pairs of LEDs and photo-resistors per taxel. One may conclude from this example, that the design of the sensor hardware and the required manufacturing processes have to be scalable in order to enable the successful integration of an artificial skin into a robotic system.

Scalability of the manufacturing processes The scalability of the artificial skin requires a scalable manufacturing technology. Therefore, the required manufacturing technology can not be considered as an independent step in the development of artificial skin but has to be developed simultaneously to the design of the sensor setup. The importance of the scalability of the manufacturing processes can be exemplified by the following example: Hasegawa et al. [51] present the fabrication process for a tactile sensor based on a woven fabric. While the approach to fabricate a tactile sensor out of a woven fiber in principle allows for the implementation of tactile sensors with scalable size the required manufacturing of the fibers restricts the size of the sensor. The highly sophisticated metallization process requires costly machinery, e.g. a sputtering apparatus contained in a vacuum chamber. In order to enable the uniform deposition of the metal on the fiber, the fibers have to be rotated during the metallization process inside the vacuum chamber. Thus, the size of the vacuum chamber restricts the maximum length of the fibers that can be metallized in one manufacturing step which in return limits the size of the sensor that can be woven out of the fibers. Consequently, the surface area that can be covered with the resulting tactile sensor is affected by the insufficient scalability of the fabrication process. The above described example demonstrates that the underlying manufacturing process can constrain the scalability of the resulting sensor system. Therefore, the manufacturing processes have to be scalable in order to enable the scalability of the resulting tactile sensor system. Sekitani et al. [142] identify the lack of scalability of the applied manufacturing technology as hindering for the development of tactile sensors for large surface areas. The authors propose a direct printing process based on conductive ink as a possible solution for scalable sensors. Ulmen and Cutkosky [166] present a tactile sensing array based on the acquisition of changes in capacitance. The authors state, that one of the objectives of the presented approach is to enable a sensor that is

> "scalable, with relatively few interface wires, enabling coverage of the entire robot surface".

Wile the authors claim scalability for the presented sensor design, each individual taxel of the prototype requires a separate readout wire that has to be manually soldered to the steel mesh acting as sensing electrode. Thus, a scaling up of the sensor size to the surface area of a humanoid robot would result in an extremely large number of required readout wires.

3.2.4 Goal conflicts

The desired integration of an artificial skin into a robotic system posed multiple requirements for the design of the artificial skin. Especially, if a whole-body artificial skin for a robotic system is desired numerous goal conflicts arise. Ulmen and Cutkosky [166] state, that:

> "The true challenge in designing a human-friendly whole body sensitive skin is effectively combining these various desired properties."

As analyzed in Strohmayr [158] one of the most prominent goal conflicts is the desired combination of a high initial sensitivity with an overload proof and thus collision tolerant design of the artificial skin hardware. Figure 3.10 exemplifies the goal conflict between sensitivity and collision tolerance of the artificial skin design. The ability of the artificial skin to withstand collisions depends on the system's ability to absorb the energy that is introduced during a collision event. In order to enable a safe pHRI passive and active measures for the reduction of collision severeness are required. Passive severeness reduction measures can be based on compliant cover layers for robotic systems. Ulmen and Cutkosky [166] state, that:

> "Some artificial skins have excellent energy absorption properties [...] However, this is typically at the cost of dynamic response and increased hysteresis [...]".

The active measures for collision severeness reduction require a high sensitivity and a short reaction time of the artificial skin. The analysis of the current state

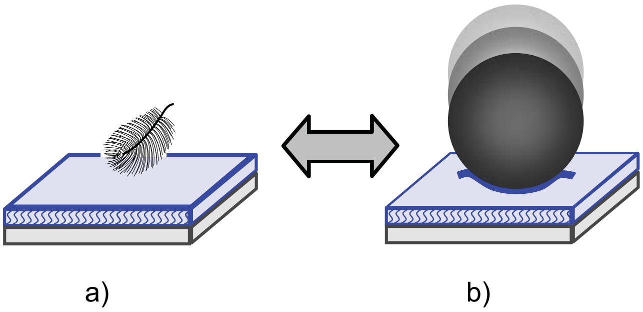


Figure 3.10: Initial sensitivity conflicts robustness. Uniting a high initial sensitivity with a collision tolerant design is prerequisite for the application of an artificial skin in real world applications on a robotic system.

of technology suggests, that the required sensitivity of artificial skin for robotic systems depends on the designated application site on the robotic system and the specific task at hand. Thus, a generalization e.g. to a $1\ g$ minimum required sensitivity would be misleading. Especially, if tradeoffs with respect to integrability and robustness have to be accepted in order to achieve this arbitrarily defined required sensitivity. Therefore, the design of artificial skin has to aim for the optimal combination of properties at the least acceptable sensitivity for the specific application site and task.

A second conflict of goals arises from the desired reduction of the reaction time and the required maximization of the information content that can be derived from the artificial skin. In order to convey a as much tactile information from the artificial skin to the control system of the robot either a high number of readout wires or a preprocessing within the artificial skin is required to enable a serial transmission of the information via a small number of readout wires. Jacobsen et al. [57] state, that

> "Critical trade-offs exist between the operating speed and the number of electrical wires in a conduit."

Therefore, in section 3.2.7 concepts for the solution of the goal conflicts are derived. In the following the implications of the operation of tactile sensors on robotic systems to the design of an artificial skin are investigated.

3.2.5 Operation on robotic systems

For a long term operation of artificial skin on robotic systems in real world applications the required robustness of the sensor hardware has to be combined with the desired high initial sensitivity.

Robustness of the sensor hardware The surface of extrinsic sensors is subject to mechanical loading. Already in 1988 Jacobsen et al. stated, that

> "The entire [tactile sensor] system must be robust enough to withstand the shocks and vibrations that are unavoidable in research and industrial environments."

Figure 3.11 illustrates the challenge of the introduction of the artificial skin on top of the supporting structure of the robotic system. Unintended physical interaction (collisions) of robotic system with rigid objects in the environment results in high local contact forces that are capable to mechanically destroy the support structure. Exemplarily, the damaged carbon fiber based covering structure of DLR light weight robots (DLR LWR III) is depicted in figure 3.11. Therefore, an artificial skin that is mounted on top of the mechanical support structure of a robotic system mechanically has to withstand collisions. Many of the currently presented sensor

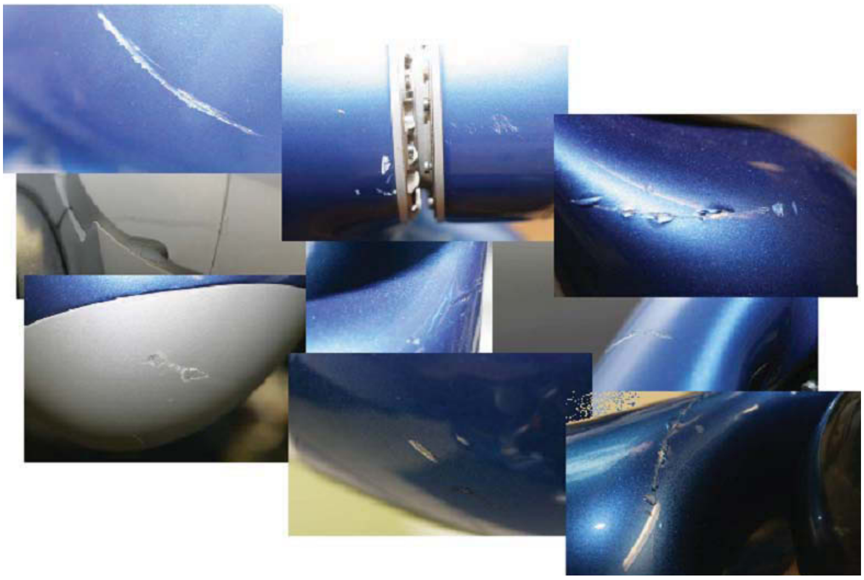


Figure 3.11: Collision of robotic systems with obstacles in the environment can cause the mechanical destruction even of the rigid covering structure of the robotic system. The above figure illustrates the consequences of collisions of DLR-LWR III with the environment

prototypes lack mechanical robustness and thus prevent a successful operation on robotic systems. An exception is the tactile sensor system presented by Göger et al. [40] which is mounted on the cylindrical and planar surfaces of a humanoid robot. The authors state, that the presented tactile sensor system is

> "[...] very robust and insensitive against mechanical overload; this is a precondition to detect and to survive collisions."

According to Haddadin et al. [47], in case of collisions between robots and their environment, collision forces up to $2.5kN$ have been measured for robot manipulator velocities of up to $2m/s$. Therefore, an overload proof design of artificial skin sensor is proposed. Figure 3.12 depicts the general categories of mechanical load types that can act upon tactile sensors. Tactile sensors in real world application are subject to blunt impacts, figure 3.12(a), shear forces, figure 3.12(b), abrasion, figure 3.12(c) and cutting by sharp or pointed objects, figure 3.12(d). The large variety of possible causes of mechanical failure of the artificial skin shows, that irrespective of the ability of the artificial skin to withstand collisions, wear and tear of real world application on a robotic system will result in mechanical damages of the artificial skin surface. In this sense Speeter [153] concludes:

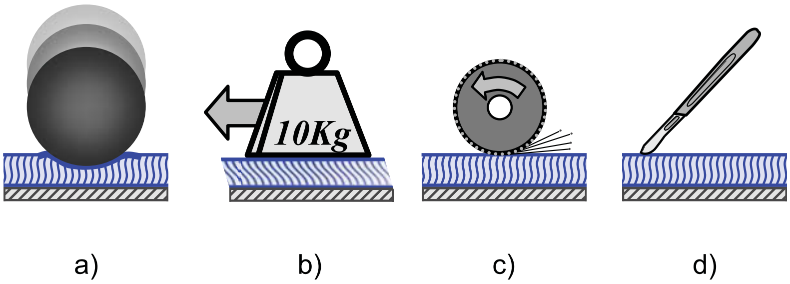


Figure 3.12: Artificial skin in real world application is subject to various mechanical load scenarios. Besides mechanical overload (a) and shear forces (b) during unintended collisions, abrasion (c) and cutting by sharp object (d) endangers the integrity of the mechanical setup of an artificial skin.

> "Tactile sensors applied to robotic hands are subject to continuous wear and abrasion and can be expected to fail after prolonged use. For this reason, sensors that are easily and economically replaced offer significant advantages over the lifetime of a system".

Artificial skin lacks the ability of biological skin to react to abrasion or injury. The absence of self-healing or regrowth processes necessitates the exchange of artificial skin that is subject to wear and tear in real world application. Thus, already during the design of the artificial skin systems the exchange of worn artificial skin components has to be anticipated. A technical equivalent to biological regrowth might be the introduction of an exchangeable superficial protection layer, that is replaced on a regular basis in order to prevent the mechanical abrasion of the underlying artificial skin and thus enable the long term operation of artificial skin on a robotic system.

High initial sensitivity The required sensitivity of tactile sensors is controversially discussed. The analysis of the state of the art suggests, that the required performance depends on the performance of the respective tactile sensor of the publication. The probably most cited sensitivity is the one introduced by Harmon [50] in 1982 . The majority of publications cite the study of Harmon overly abbreviated with $1\ g$ required sensitivity. Harmon himself summarizes the results of a questionnaire with respect to sensitivity as:

> "The degree of sensitivity required depends on application. Again, interrelationships among variables were stressed; mass, velocity, acceleration, response time, and strength of materials are mutually dependent design parameters relevant to sensitivity requirements as well as to stability criteria. Among other considerations, a touch sensing transducer and its appendage must not move or damage a touched (or collided with) object. This depends first-order on the touched object's mass and hence is specialized for an application at the start. Most light assembly tasks were seen to require force sensitivity (for each matrix element) of at least one or a few grams. A few respondents saw $0.5\ g$ as desirable, while others said they would be content with $5 - 10\ g$."

Mannsfeld et al. [94] present a highly sensitive tactile sensor array based on the acquisition of changes in capacitance. The authors differentiate between medium pressure sensitivity, ranging from $10\ kPa$ to $100\ kPa$ and low pressure sensitivity for pressures below $10\ kPa$. According to the authors the medium pressure sensitivity is sufficient e.g. for manipulation tasks, while low pressure sensitivity corresponds to a gentle touch. With respect to the determination of the pressure level of a gentle touch the authors refer the reader to the work of Dellon et al. [23].

Peine and Howe [119] request an even higher pressure sensitivity of $0.5\ kPa$ for technical palpation devices. The authors argue, that, in order to enable the restoration of tactile sensing capabilities of surgeons during minimally invasive surgery, the tactile sensing system at least has to meet the sensitivity observable in human fingertips.

One may conclude from the diversity of requested sensitivity of an artificial skin that the actually required sensitivity depends on the application site on the robotic system and the specific task. Therefore, the design of the artificial skin concept is focussed on the adaptability of the transduction properties rather than to aim for the highest possible initial sensitivity.

Adaptable transduction properties To enable the successful operation of an artificial skin on a robotic system the range of the sensitivity has to be scalable in order to fit the site-dependent requirements. Each of the application sites on a robotic system poses different requirements for the covering artificial skin sensor, e.g. high spatial resolution combined with high initial sensitivity on robotic fingertips or a high pressure range on the soles of a robot foot. Lai et al. [77] propose a tactile sensing array with dynamically tunable transduction properties. The sensing principle is based on the acquisition of the volume resistivity of a compound of carbon nano tubes (CNT) dispersed in liquid crystal. The authors state, that based on changes in the applied voltage the measurement range of the taxels can be tuned. The major limitation of the proposed sensor setup is the applied glass substrate which renders the sensor frail and limits the application to planar geometries. The presented approach enables the dynamic adaptation of the transduction properties. While this functionality might be beneficial e.g. for the adaptation of the sensor to specific tasks, it is not necessary for the implementation of artificial skin with transduction properties adapted to the application site on the robotic system. Therefore, a concept for a static adaptation of the transduction properties prior to the integration into a robotic system is proposed. The range of expected indentation force or pressure depends on the site of application. For the example of humanoid robotic systems the expected indentation forces range from a light touch at the robotic fingertip, figure 3.13(a), over the interaction forces exerted on a robotic arm, figure 3.13(b) during pHRI, to high local forces at the soles of the robotic foot during biped locomotion, , figure 3.13(c). Therefor the measurement range has to be adapted to the requirements of the application site. The expected indentation forces for robotic fingertips are defined by the maximum applicable force of the actuator of the robotic finger. The maximum fingertip e.g. of the DLR Hand II reaches $30\ N$, e.g. Butterfass et al. [11]. Therefore, the measurement range of an artificial skin may be limited to $30\ N$ per taxel, which corresponds to the worst case, the indentation of the artificial skin with maximum fingertip force on the surface area of a single taxel. The measurement range for an artificial skin on the sole of a robotic foot can be estimated from the weight of the robotic system, and the surface area of a single foot, e.g. the DLR Biped Robot presented by Ott et al. [113].

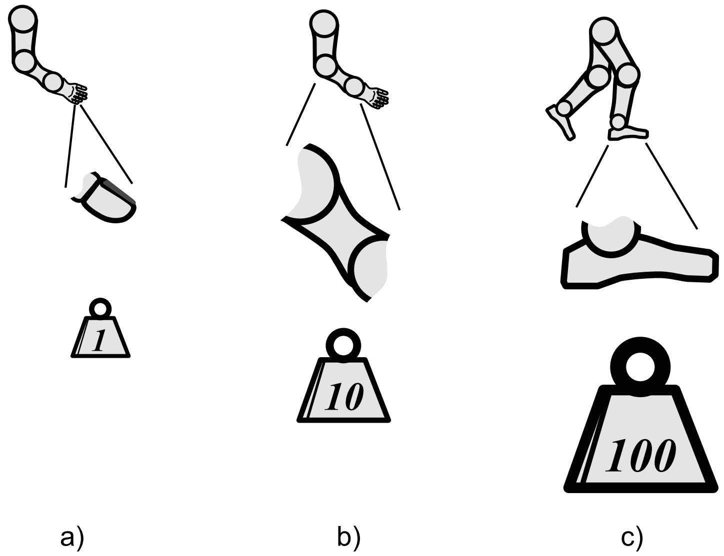


Figure 3.13: For the successful operation of artificial skin on robotic systems the measurement range of the artificial skin needs to be scalable to enable the adaptation of the transduction properties to the requirements of the application site on the robotic system. Hence artificial skin for robotic fingertips requires a high initial sensitivity while a measurement range up equaling the maximum excertable force of the robotic fingertip is sufficient (a). For a robotic arm structure (b), the measurement range needs to be adapted the the planned tasks, e.g. a pHRI based on tactile input from the human user would require a higher sensitivity as would a task where only a collision detection has to be enabled. Accordingly the measurement range of an artificial skin for the soles of a robotic foot depends on the weight of the robotic system as well as from the dynamics the robotic system is capable of, e.g. for slow walking a smaller measurement range is required than for a highly dynamic running system.

According to the authors the overall weight of the robotic system is $49.2\ kg$, and a surface area of $95\ mm \times 250\ mm$ for one sole of foot . Thus, the static indentation forces on the sole of a robotic foot are about $480\ N$ resulting in a static pressure of approximately $20\ kPa$ for a single footed stance. These examples show the variation of the required measurement range according to the site of application. For the design of an artificial skin for robotic systems one may conclude, that the measurement range of the artificial skin has to be adaptable. Therefore, already during the derivation of the concept of the artificial skin the adaptability of the transduction properties has to be anticipated.

3.2.6 Sensor data acquisition

The design of the sensor data acquisition strategy for the artificial skin has to enable the successful operation on robotic systems in real world applications. One has to consider the constraints arising from the spatial integration into a robotic system.

In order to enable the useful application of the tactile information derived from the artificial skin for motion control of a robotic system, the artificial skin has to be optimized with respect to reaction time and data rate. Jacobsen et al. [57] identified the reduction of the number of readout wires as crucial for the implementation of reliable tactile sensor systems for real-world application. The authors state, that

> "Contact data from many sites must be transferred to the controller at rates sufficient for tactile information to be successfully used in dynamic end-effector control, yet since conduit routing and fatigue will play a major role in system reliability, the system should be designed to minimize the number of data conductors used."

In the same sense argue Engel et al. [31, 30], who present a multi-functional artificial skin based on a bendable Kapton® substrate. According to the authors, the setup is capable of acquiring "temperature, hardness, force, thermal conductivity, and curvature". Each of the so called sensing nodes requires ten readout wires, therefore the authors conclude, that:

> "[...] the utility of this sensor skin is limited by the scalability of the wiring interconnects".

Therefore, the reduction of the number of required readout wires is one of the major challenges for the design of an artificial skin system capable to cover the entire surface of a robotic system. Within this thesis an approach based on the minimization of the amount of data that is acquired at the first hand is pursued. The goal of the development is the minimization of the number of required readout wires without compromising the required information depth. Therefore, the size and shape of the individual taxels is adapted to the requirements of the application site on the robotic system.

Adaptable spatial resolution In order to minimize the acquisition of redundant tactile information the size and shape of the individual taxels has to be adapted to the requirements of the application site, see figure 3.14. The varying two-point threshold in human skin is visualized in the so called Weinstein-Maps, e.g. described in Myles and Binseel [101]. They represent the distribution of the two-point threshold and the initial sensitivity over the human body. The analysis of the dispersion of sensory cells over the human body shows, that the dispersion is highly variable and adapted to the needs of the body site. The highest initial sensitivity in human skin can be observed in the skin of the lips and the fingertips. The two-point threshold is minimal in these regions. This principle can be adopted for the development of artificial tactile sensing systems. In order to do so, the design of the

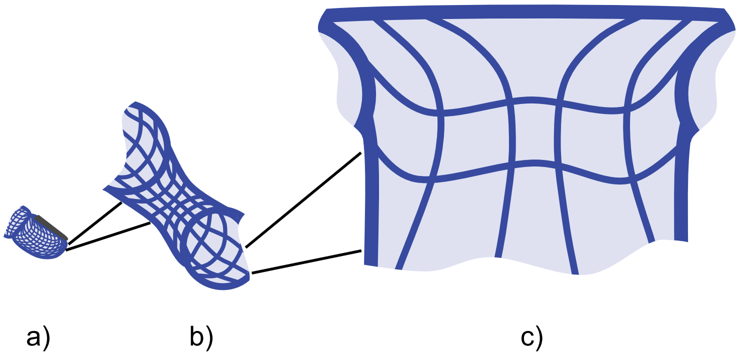


Figure 3.14: The size of a single taxel is compared for a robotic fingertip (a), the structure of a robotic arm or manipulator (b), and the torso of a humanoid robotic system (c). The scalability of spatial resolution according to body site is a prerequisite for the desired minimization of the amount of data that has to be preprocessed and transferred to the control unit of the robotic system. The basic idea is the reduction of the spatial resolution to the minimum required resolution according to the application site on the robotic system.

artificial skin sensor has to enable a scalable spatial resolution for the application on various sites on the robotic system. With respect to humanoid robot systems the required spatial resolution of artificial skin ranges from sub-millimeter resolution at the lips and fingertips, figure 3.14(a), over a resolution of tens of millimeters on a robotic arm, figure 3.14(b), to a spatial resolution of up to $70mm$ for the covering of large surface areas as a the torso of a humanoid robotic system, figure 3.14(c). For the acquisition of tactile data from large areas e.g. the torso of a humanoid robotic system the information regarding the contact location within the surface area of an individual taxel is not necessarily relevant. Whereas the indentation with pointed object has to be detected reliably irrespective of the contact location. This requires an equally distributed sensitivity over the surface area of each individual taxel. Therefore, the extension of insensitive surface area within the sensing surface has to be minimized. The ratio of sensitive versus insensitive areas is a measure of the sensory performance of artificial skin sensors and can be defined as:

$$SIR = \frac{A_{sensitive}}{A_{skin}} \tag{3.1}$$

Where the ratio of sensitive area $A_{sensitive}$ to the entire sensor area A_{skin} is referred to as SIR. Hence the design of the artificial skin as well as the underlying manufacturing processes have to enable the implementation of scalable taxels with adaptable surface area and a SIR close to one.

To enable the acquisition of the required detailed tactile information and at the same time minimizing the number of the required readout wires different contacting principles for the connection of the individual taxels are proposed in literature.

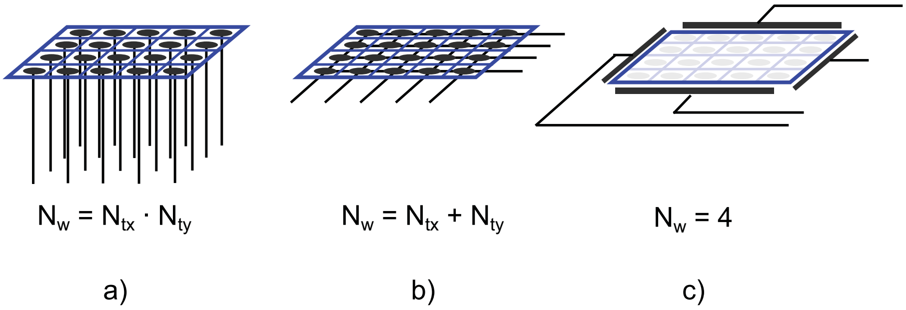


Figure 3.15: General contacting principles for the connection of the taxels of an artificial skin. Individual contacting of the taxels (a), results in a minimal cross influencing of the taxels and thus enables a straight forward acquisition of tactile information. The arrangement of the taxels in a matrix configuration (b), results in cross influencing of the individual taxels requiring compensation in the readout circuit. The maximum reduction of the number of readout wires is achieved if the sensitive area is contacted at the rims only (c). While enabling minimal numbers of readout wires, this approach results in the reduction of the achievable spatial resolution and reduces the ability of the sensor to detect multiple simultaneous indentations.

Figure 3.15 depicts the general contacting principles applied in tactile sensing hardware. A straight forward principle is the electrical connection of each individual taxel, figure 3.15(a), e.g. Weiss et al. [177], Ulmen et al. [166] and Oballe-Peinado et al. [108]. Alternatively, the individual taxels can be addressed through a matrix configuration of the readout wires, figure 3.15(b), e.g. Strohmayr et al. [159]. The application of a matrix configuration results in undesired cross correlation of the individual tactile elements. The effects of a matrix configuration of a resistive tactile sensor have been analyzed in Schnös [135]. Schnös proposes a strategy to account for the systematic measurement error arising from the matrix configuration of the readout wires. If taxels are connected in a matrix configuration sequential readout strategies have to be applied. Thus, the derived information from the spatially distributed taxels is subject to temporal delay. This effect limits the significance of the information derived from the tactile sensing array. Therefore, the increase of the scanning rate of the matrix configuration is crucial for the validity of the tactile information. With respect to the utilization of the tactile information for the control of a robotic system the reaction time of the artificial skin sensor system is essential.

An extreme reduction of the number of readout wires is shown by Alirezaei et al. [2] who propose an approach based only on a fix number of readout wires connected to the rim of a sensitive surface, figure 3.15(c). The scaling up of the sensor surface area thus would not increase the number of required readout wires but decrease the achievable spatial resolution. The major drawback of the presented approach is the comparatively low spatial resolution and the restricted ability to detect multiple simultaneous indentations.

The above examples show, that the reduction of the number of readout wires results in undesired effect impairing the performance of the resulting sensing system. Therefore, a tradeoff between the number of readout wires and the quality of the transduction properties is inevitable. Within this thesis an approach for the sensor data acquisition based on a matrix configuration of the sensitive area is pursued.

Readout concept The acquisition of tactile information from artificial skins can not be considered individually as an isolated process but has to be understood as an integral step in the design of the artificial skin hardware. The design of the sensor data processing constraints the design of the transduction hardware and vice versa. Following a concept for the sensor data acquisition in artificial skin is derived that accounts for the constraints of the desired functional and spacial integration into a robotic system. Tactile information can be derived from data that is acquired from: A single taxel, figure 3.16(a) and the variation of the activation of a single taxel, figure 3.16(b). Based on the acquisition of multiple taxels, figure 3.16(c),and their course of activation, figure 3.16(d). In addition tactile information can be derived from sensor data fusion, figure 3.16(e). For the processing of tactile

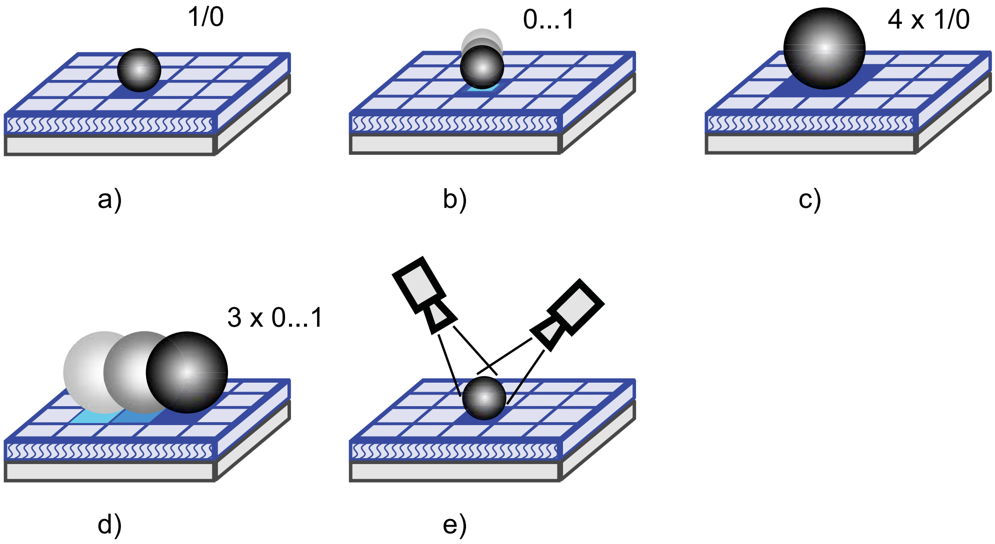


Figure 3.16: Tactile information can be categorized according to the modus of acquisition. The acquisition can be based on data from a single taxel (a), the variation of a single taxel (b) or a group of taxels (c), and the variation of their activation status (d). In addition tactile information can be derived from sensor data fusion (e).

sensor data it is important to distinguish between information that can be derived from a single taxel and information that requires data derived from multiple taxels. The derivation of information based on tactile data stemming from multiple taxels constraints the development of the required readout electronics, as e.g. the time delays in an sequential readout of multiple taxels affects the validity of the derived information. Additional information can be derived by assessing the changes of the data from the taxels over time. Data processing strategies, e.g. optical flow analysis can be adapted from image processing. Finally, information can be derived by the fusion of data from different sensor types, e.g. intrinsic sensors within the robot structure, tactile surface sensors and external vision systems.

Figure 3.17 depicts the standard configuration of a redout circuit for the acquisition of tactile information from a resistive tactile sensor. To increase the ability of a robotic system to adequately react to contact events, e.g. an undesired collision the time required for the artificial skin to reliably detect the contact event has to be reduced. For this thesis the reaction time T_R is defined as the time span between the initial contact of an object with the surface of the artificial skin and the provision of a stable contact detection signal from the readout circuit. The reaction time depends on the time required for the acquisition of the current activation status of an individual taxel T_S. Irrespective of the applied transduction principle this time

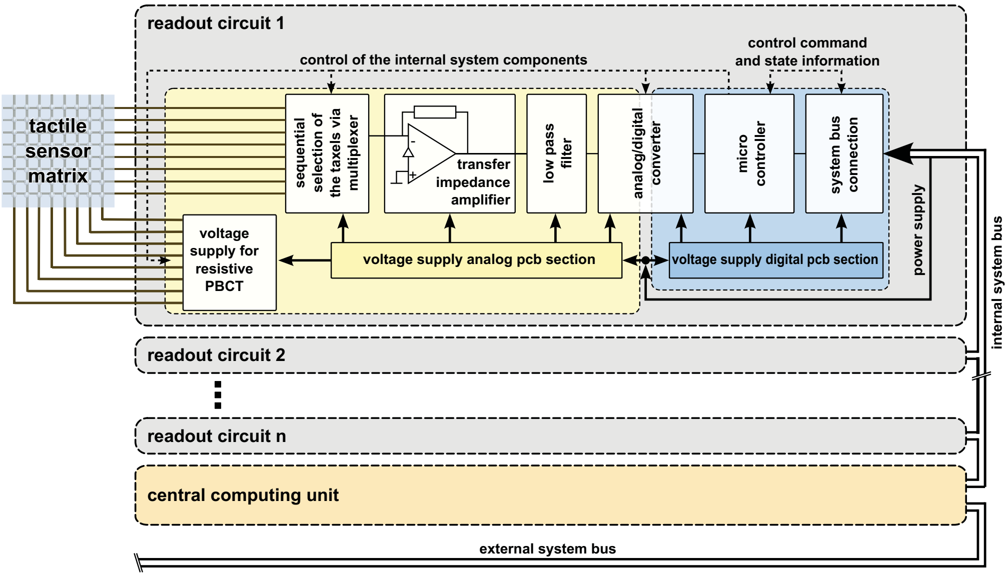


Figure 3.17: Design concept for the standard readout electronics, for multiple sensor patches. The figure exemplarily depicts the setup for the acquisition of tactile information from a resistive tactile sensor in matrix configuration. Figure adapted from Schnös [135].

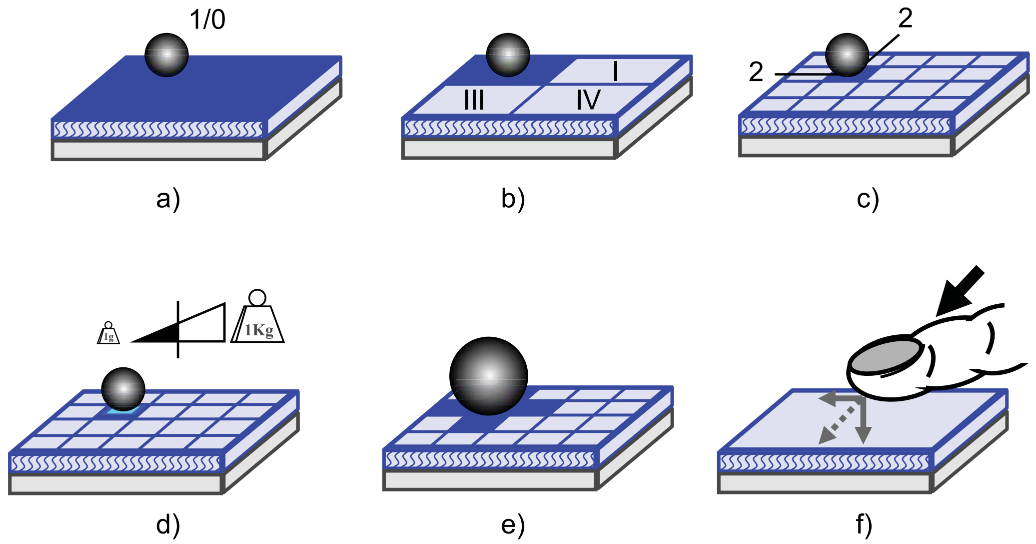
span can not be reduced infinitely. Thus, the acquisition time of the activation status of an entire sensor patch T_P depends on the number of taxels to be scanned. A sensor patch is defined as the portion of the artificial skin that is connected to a single redout circuit. In addition, the time required for the transmission of the data to the control system T_S adds to the overall reaction time. Thus, for the reduction of the reaction time of the artificial skin the amount of tactile data relayed to the control of the robotic system has to be minimized. Jacobsen et al. [57] propose a strategy for the reduction of the amount of data that has to be transmitted to the control of the robotic system. The authors hint, that a "full scan" of all tactile sensing elements of the sensor system within a single time interval of the data acquisition prevents the scaling up of the number of taxels and thus limits the size of the tactile sensor system. Therefore, the authors propose the utilization of a so called "reactive scan" or an "anticipatory scan". The reactive scan can be based on the focus of the data acquisition from taxels that have recently been activated. While this strategy might be beneficial during e.g. slow finger movements in the pick up phase during object manipulation. The focus on past contact events is unlikely to improve the performance of the tactile sensor system during high speed motion of the manipulator of the robotic system. Therefore, the authors propose a so called anticipatory scan where e.g. the sensor patches on the fingertips during the approach phase of object manipulation are scanned at a higher frequency. The major drawback of this approach is the inherent reduction of reliability as individual taxels or groups of taxels are rendered more important than others.

In order to resolve the goal conflict between the desired reduction of the reaction time and the reliability of the acquired tactile information, a readout strategy based on the sequential increase of information content is proposed. A strategy for the increase of the sampling rate of the resistive array sensor based on variable resolution is proposed by Speeter [153]. Speeter concludes, that

> "An additional feature of piezoresistive grid sensors, not unique to FSR, is the ability to vary resolution by joining rows and columns with shunts. The electronics required are simple and provide a powerful technique for dynamic reconfiguration and control of maximal data sampling rates. [...] By lowering the resolution, very high data rates can be achieved, possibly allowing slip detection and vibration detection without specialized sensing apparatus."

The implementation of the variable resolution is based on the application of multiplexers and analog switches enabling the electrical contacting of individual rows and columns. The basic idea is the provision of a reduced amount of information at a high update rate. Subsequent to a detected contact event the content of infor-

mation is sequentially increased at the cost of an increase in reaction time.
Figure 3.18 depicts the working principle of the sequential increase of information content. Starting from the provision of a binary "early-warning" contact information for the entire sensor patch, figure 3.18(a). Subsequently, the sensor patch is divided in quadrants with decreasing size until the exact location of the contact event is determined, figure 3.18(b,c). Following, the activation level of the contacted taxel is evaluated, figure 3.18(d), and the spatial extension of the contact surface area determined, figure 3.18(e). Finally the exact characteristics of the contact event are derived from the data acquired by a multitude of specialized taxels, e.g. the determination of the direction of the resulting indentation force vector form normal and shear force sensitive taxels, figure 3.18(f). In order to implemented dynamically adaptive receptive fields the standard configuration of a readout circuit, see figure 3.17, of a resistive tactile sensor matrix is optimized. Instead of applying multiplexers that allow only for the sequential acquisition of individual taxels the application of analog matrix switches is proposed that allow for the dynamic adaptation of virtual receptive fields within a sensor patch. This hardware based approach forms the basis for the application of the strategy to minimize the amount of acquired data in order to reduce the overall reaction time of the artificial skin without compromising the reliability of the derived information.



a) b) c) d) e) f)

Figure 3.18: The minimization of the reaction time of the artificial skin to a contact event is based on a readout strategy that allows for the sequential increase of information depth.

In addition to the proposed sequential increase of information content, within this thesis the strategy of the anticipatory scan, proposed by Jacobsen et al. [57] is generalized towards a motion dependent tactile attention. Based on the planned trajectory of the robotic system sensor data is acquired from individual taxels or sensor patches at a scanning rate dependent of the likeliness of a contact event on these areas of the tactile sensor system. However, this approach does not apply for impacts which occur trough moving objects. An example is the acquisition of sensor data from the taxels that are located on the outside of an outward moving elbow at an elevated scanning rate. Due to the outward motion of the robotic elbow the likeliness of the occurrence of a contact event is higher for the taxels in motion direction. The likeliness of a contact event on a specific taxel or sensor patch can be estimated from the angle between the surface normal of the taxel and the motion direction of the robot segment the taxel is mounted on. Based on this strategy a motion dependent robotic tactile attention can be implemented in the form of an enhanced sensitivity and readout frequency of tactile surface sensor elements with surface normals that are oriented in the motion direction of the structure they are mounted on. In order to enable the implementation of the motion dependent tactile attention the robotic system has to offer information regarding the current and planned motion of the individual segments. To minimize the communication load, the processing of the segment motion information can be located in the control system of the robot, thus only the information which taxels are currently and will in near future be oriented in the direction of motion of the robot. The readout electronics can react accordingly and reconfigure the receptive fields and thus adapt the selective tactile attention by increasing the local readout frequency in order to decrease the reaction time after a collision detection. On the other hand, the current configuration of the virtual receptive fields can be fed back to the robot control system in order to actualize the information where the tactile attention is focused to and thus create an a priori knowledge which receptive field has detected a physical contact if the digital "early warning" signal is enabled.

3.2.7 Artificial skin concept

Following a general concept for an artificial skin for robotic systems is derived based on the lessons learned during the development of tactile sensors previous to this study.
Previous to this thesis a variety of tactile sensors based on various transduction principles has been investigated at DLR. The principle setup is described e.g. by van der Smagt [149].The tactile sensor prototypes manufactured by Saal [129] have been analyzed on a testbed designed in Strohmayr [158]. The results of the indentation tests have been published in Strohmayr et al. [159]. While the manufactured tactile sensor prototypes offered the desired high spatial resolution, the conducted experiments revealed a set of disadvantages. The most critical being the observed non-monotony of the output signal. If the sensor patch was mechanically compressed on the testbed an unexpected initial increase of electrical resistivity was observed. The further increase of the indentation force resulted in the expected decrease of electrical resistivity. An examination based on light microscope inspection and scanning electron microscopy (SEM) revealed an unsatisfactory adhesion between the molded-in metal wires and the particle-filled polymer, see figure 3.19. Additional indentation testing revealed that the polymer matrix at the crossing points was cut by the metal wires due to repetitive mechanical indentation of the tactile sensors on the testbed. A conducted overload test showed, that the combination of polymer sensor material and metal based readout wires in the mechanically loaded area of the tactile sensor resulted in the mechanical destruction of the tactile sensor prototypes. The severity of the discovered limitations and disadvantages encour-

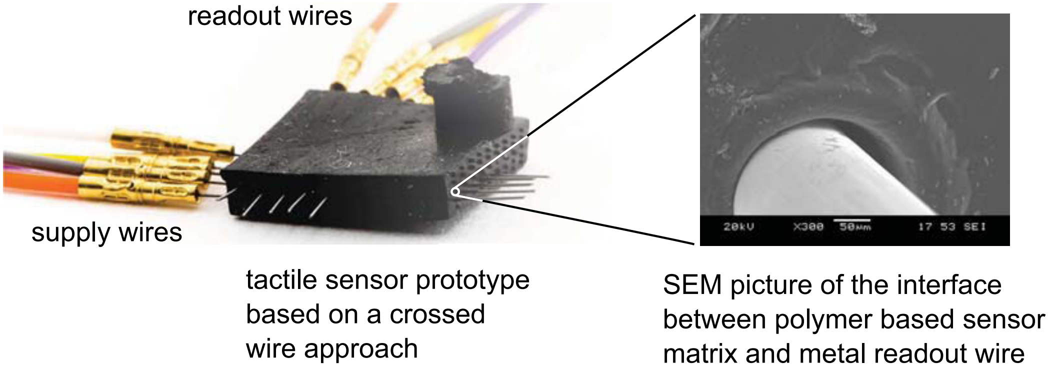


Figure 3.19: Prior to this thesis a tactile sensor concept based on a crossed-wire approach has been pursued. The SEM pictures revealed an unsatisfactory mechanical adhesion between the polymer matrix of the sensor and the metal based readout wires, figure adapted from Strohmayr et al. [159].

aged the questioning of the entire initial approach. The lessons learned from the analysis of the described approach can be summarized as "How-NOT-To" design a tactile sensor:

- DO NOT – Focus on high spatial resolution.
- DO NOT – Integrate the physical hard-soft interface between metal based pathways of the readout electronics and polymer inside the mechanically loaded sensing area.
- DO NOT – Design a manufacturing process that requires time consuming preparation and interchange of the required tools if the spatial resolution has to be altered.
- DO NOT – Combine this manufacturing process with costly specialized tools
- DO NOT – Apply a manufacturing process that prevents the adaptation of the sensor with respect to a change in sensor size and shape.
- DO NOT – Apply a solid polymer volume as transduction medium.

Nevertheless, the conducted experiments and the analysis of the literature led to the identification of the following fundamental challenges for the design of an artificial skin for robotic systems.

Design paradigms

The key challenge for the design of artificial skin sensor systems is the solution of the conflicts of goals that arise from the combination of the requirements. One of the most prominent goal conflicts arises from the combination of the required collision tolerant sensor hardware and the desired high initial sensitivity. Following a set of design paradigms is proposed to enable a solution of the conflicts of goals.

All-polymer sensor design The required mechanical properties presented in chapter 1 suggest the application of polymer materials for the design of the sensitive structure of artificial skin sensors. Two major advantages arise from the application of polymer material. Firstly, polymers enable the design of stretchable sensor hardware that can be applied on 3D curved surfaces of, e.g. the outer surface of modern humanoid robot systems. Moreover, a stretchable polymer based design of the sensitive layer may help to create sensors that are fit for mass producibility. Secondly, the application of polymers allows for the design of durable artificial skin sensors that can be located upon a mechanical damping layer. This enables an overload proof design of the artificial skin sensors that is capable to withstand the effects of collisions between the robot and its environment. The interaction of metal conductors and polymer based materials for the design of compliant tactile sensors is investigated in Strohmayr [158]. The study showed, that if such senors are mechanically loaded with high pressures a relative movement between the rigid metal based readout wires and the surrounding compliant polymer material is induced. The relative movement results in the destruction of the polymer material at the crossing points of the sensor matrix. From these findings one may generalize, that a design approach entirely based on the application of polymer material for an artificial skin may lead to a collision tolerant design. To enable an overload proof artificial skin that can withstand high external pressure, the introduction of rigid elements, e.g. metal readout wires, standard resistors etc., into the sensing surface has to be avoided. In addition, the application of a protective top layer that distributes the indentation forces of sharp objects to a larger surface area can help to reduce maxima in local pressure. More general, an all-polymer design approach may enable the implementation of overload proof artificial skin and thus forms the basis for the solution of the most prominent conflict of goals. Following, design paradigms for an increase of the sensitivity of an artificial skin area outlined.

Volume reduction A conflict of goals arises if high initial sensitivity and robustness of the artificial skin sensor surface are required at the same time. Many of today's tactile sensors, presented in the current literature reviews, e.g. by Dahiya et al. [20], are impeded by their lack of high initial sensitivity. The initial sensitivity can be defined as the threshold of energy that has to be introduced to the artificial skin sensor in order to evoke a detectable sensor output. The acquisition of the mechanical domain of a contact event through tactile sensors often depends on the displacement or a material deformation that is required in order to create a sensor output signal. The required displacement or deformation depends on the mechanical setup of the sensor as well as on the transduction principle. Hence the sensitivity of the artificial skin sensor depends on the overall volume that has to be deformed for the transduction. In order to decrease the required input energy threshold, the material volume that has to be deformed has to be minimized. The deformed volume reduction of a solid polymer material, figure 3.20(a) can be based on two principles. Via material density reduction by the application of low density materials, e.g. polymer foams, figure 3.20(b) or, via the reduction of the designed density, see figure 3.20(c). Based on an approach similar to the setup proposed by Wettels et al. [181, 180], Berselli et al. [7] present an approach towards the reduction of the material volume in order to minimize the normal indentation force that is required to generate the desired deformation of a soft polymer based fingertip. Design density is a measure for the ratio between applied solid polymer material

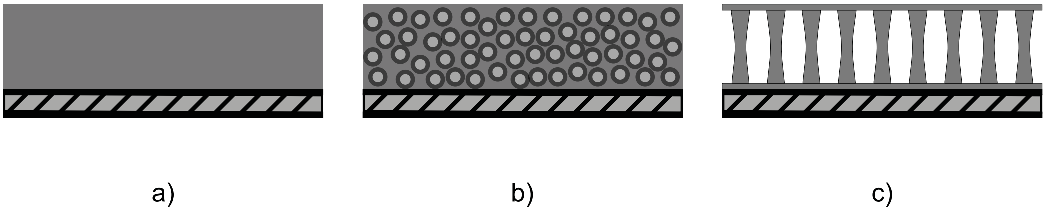


Figure 3.20: The required deformation energy can be reduced if a solid polymer material with small elastic modulus is applied, material density (a), e.g. Strohmayr et al. [159]. A second approach is the application of open or closed cell foams that introduce randomly arranged voids into the polymer material, compound density (b), e.g. Fritzsche et al. [35] or Cannata et al. [12]. The third approach, pursued in this thesis, is based on the introduction of geometrically defined voids, referred to as reduction of the designed density (c).

and incorporated unoccupied volume. With respect to artificial skin sensors the design density describes the material volume that is applied for the construction of the entire volume of the artificial skin. The reduction of the design density is based on a geometrically determined reduction of the solid volume within the sensor volume. The geometrically determined volume reduction allows for the utilization of polymer materials exhibiting beneficial material properties e.g. low mechanical hysteresis, without compromising the sensing threshold. The deformation of the polymer material requires energy input. With respect to the foreseen integration into a robotic system not all the polymer volume can be applied for the transduction of the stimulus. Thus, the setup of artificial skin sensor can be divided into sensitive and non-sensitive structures. Non-sensitive structures are e.g. required for the fixation of the sensitive elements and for the mechanical interface to the cover structure of a robotic system. The non-sensitive volume contributes to the required robustness of the artificial skin sensor. In general, the introduced energy is applied for the deformation of both, sensitive and non-sensitive, volume. Therefore, the ratio of deformed volume that contributes to the transduction of the stimulus and the volume of the non-sensitive supporting structure has to be optimized. The sensitivity efficiency factor (SEF) for the design of artificial skin sensors is introduced.

$$SEF = \frac{V_{sensitive}}{V_{skin}} \tag{3.2}$$

Where $V_{sensitive}$ represents the volume that directly contributes to the transduction of an external stimulus. The SEF relates the sensitive volume $V_{sensitive}$ to the overall skin volume V_{skin} that forms a single taxel or receptive field. If the receptive fields are separated by insensitive areas, these areas have to be added proportionately to the receptive field and thus increase the artificial skin volume. The area of overlapping receptive fields has to be subtracted accordingly. In addition to the reduction of the deformed polymer of the sensitive layer itself, the location of the sensitive layer within the overall layer setup of the artificial skin affects the quality of the information that can be derived from this sensory layer. In general, the thickness of the polymer material that covers the sensitive layer has to be minimized in order to enable a high initial sensitivity of the overall artificial skin. Summarizing, the following parameters can be optimized in order to enhance the initial sensitivity of an artificial skin sensor:

- Overall deformed volume
- Material density
- Designed density
- SEF

Functional partitioning For the design of artificial skins for robotic systems dedicated functional layer are applied in order to provide the required wide functional range. The composition of the artificial skin is based on two major skin layers. First, a mechanical damping layer that enables the deformation of the artificial skin and thus supports grasp stability or cushions involuntary collisions of the robotic system with its environment. Second, a sensitive layer that comprises the sensory capabilities and is located at the surface of the artificial skin. Figure 3.21(a), depicts the working principle of the "classical" approach for tactile sensors where the restoration force, the mechanical damping properties and the transduction properties are implemented in the homogenous setup of the tactile sensor. This setup is applied by various groups, e.g. applied by Fritzsche et al. [35] and Cannata et al. [12]. For this approach the properties of the applied material have to be optimized in order to suit the required mechanical properties (restoration force and mechanical damping) and at the same time fulfill the requirements with respect to the transduction properties. An alternative approach, figure 3.21(b), pursued e.g. by Weiss et al. [177] is based on an internal transduction layer and a superficial damping layer. The transduction is based on the acquisition of the electrical resistivity at the interface between an electrically conductive polymer and metal based electrodes. Here, the restoration forces are generated from the micro surface structure of the polymer in physical contact with the surface of the metal electrodes. This approach offers the advantage, that the transduction properties can be optimized independently of the mechanical deformation and damping properties of the

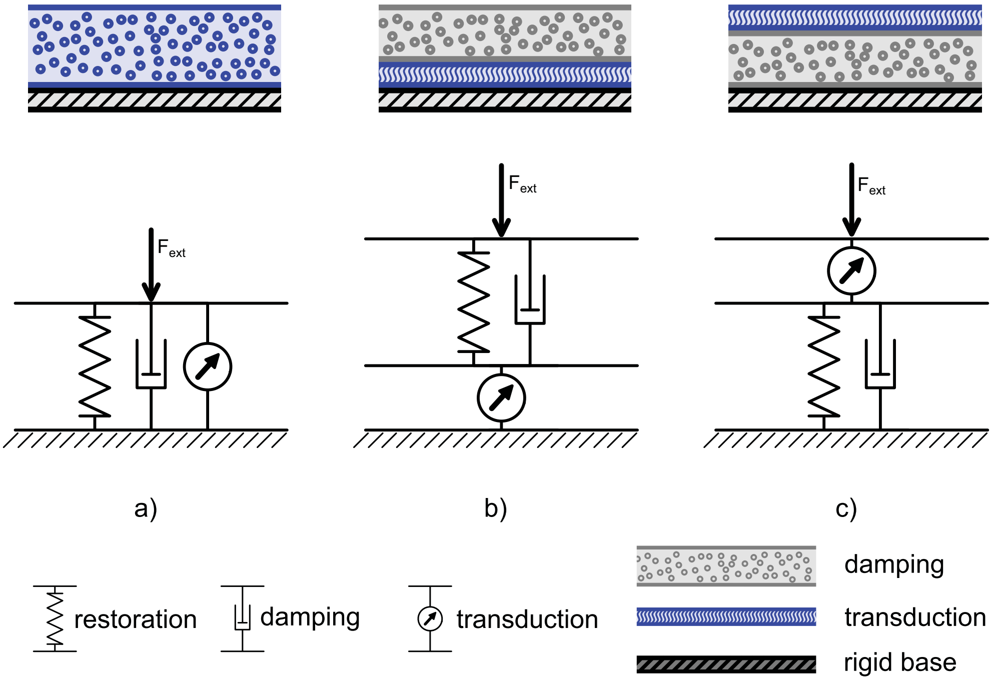


Figure 3.21: For the solution of the conflict of goals between the desired high initial sensitivity and the required mechanical robustness of the artificial skin a functional partitioning of the functional range is proposed. For the "classical" setup of tactile sensors (a) a homogeneous material is applied for the mechanical damping, the transduction and the provision of the required restoration forces. Thus, the design of the material is always subject to tradeoffs between the individual properties. In order to enable enhanced transduction properties a setup based on a superficial damping layer and an underlying transduction layer (b) is proposed by various research groups. The major drawback of this setup is the reduced initial sensitivity as external stimuli are cushioned by the superficial damping layer. Therefore, a functional partitioning of the setup of the artificial skin is proposed, (c). Based on an internal damping layer and a superficial transduction layer a setup can be derived that unites the desired high initial sensitivity with a mechanically robust design of the setup. Prerequisite for the implementation of the proposed setup is the development of a stretchable superficial tactile sensor that accounts for the deformability of the underlying damping layer.

superficial damping layer. The major drawback of this approach is the comparatively low sensitivity as the superficial damping layer has to be deformed in order to evoke a measurable change of electrical conductivity at the underlying contacting electrodes. A similar principle is applied for the approach of Wettels et al. [182]. Here the authors present a tactile sensing system integrated into the two distal phalanges of a robotic finger. In contrast to Weiss et. al. [177], here the transduction is based on the acquisition of the impedance in an electrically conductive fluid. Again, the restoration forces for the transduction layer are generated from the introduced micro-structure of the inner surface of the fluid cavity.

For the development of an artificial skin for robotic systems in this thesis the setup depicted in figure 3.21(c) is proposed. The setup consists of an internal damping/deformation layer enabling the the conformation of a robotic fingertip to a grasped object as well as the dissipation of the kinetic energy introduced in case of an unintended collision of the robotic system and an object or person in the environment. On top of the damping/deformation layer a superficial tactile sensing layer is introduced. This configuration enables the increase of initial sensitivity as a reduced material volume is to be deformed in order to evoke a measurable sensor output. Thus, the proposed setup might enable the solution of the goal conflict between the desired high initial sensitivity and the required collision tolerant design. The composition of the artificial skin out of a set of specialized layers with optimized properties is prerequisite for the derivation of artificial skin sensor systems for real world applications on robotic systems. The proposed design paradigms for the development of artificial skin for robotic systems can be summarized as:

- Base the entire artificial skin on polymer materials
- Exclude rigid components from the mechanically loaded area
- Locate the transduction layer close to the surface
- Reduce the material volume to be deformed to evoke a sensor output
- Subdivide artificial skin into functional components
- Apply specialized functional layers with optimized properties

Fingertip configuration

For this thesis artificial skin is defined as the combination of a deformable sensitive layer, the tactile surface sensor, and an underlying damping layer covering the rigid cover structure of the robotic system. The functional range of artificial skin exceeds the functionality of tactile sensors. In addition to the provision of tactile information artificial skin is capable to passively enhance safety and dexterity of the robotic system. With a focus on the design of robotic fingers Shimoga and Goldenberg [143] identify the importance of the attenuation of the impact forces in order to ensure the proper functionality of "force, tactile and slip sensors that are often located close to the finger tips". Figure 3.22 depicts the generalized setup of tactile sensors and artificial skin. On the left the 'classical' setup of tactile sensors is depicted where a sensitive layer is located directly on the rigid structure of the cover of the robotic system. The sensitive layer of tactile sensors is the often covered by a damping or protecting layer.

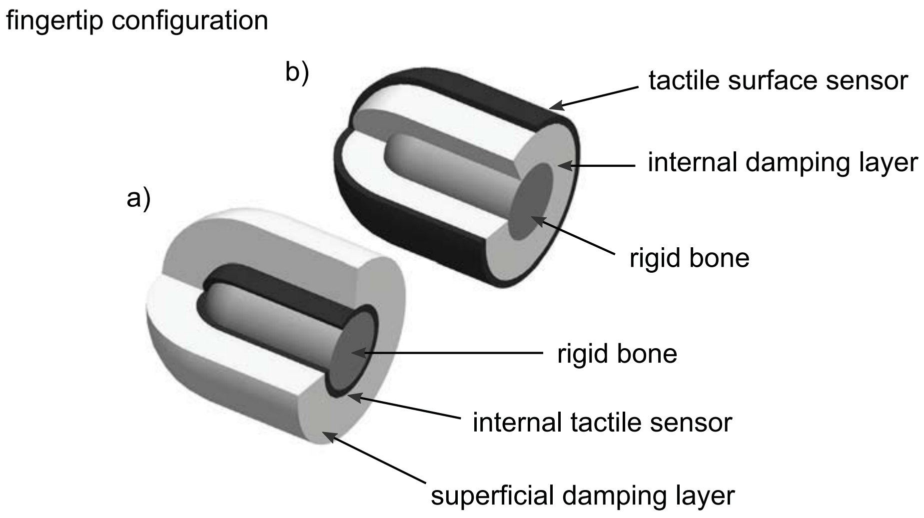


Figure 3.22: "Classical" fingertip configuration for robotic systems based on an internal tactile sensor and a superficial deformation layer. Major disadvantage of the well established setup is the minimal initial sensitivity as external indentation forces have to deform the superficial deformation layer in order to evoke a measurable signal from the internal tactile sensor. On the right the configuration of a robotic fingertip based on an artificial skin approach is depicted. The setup consist of an internal deformation layer and a superficial tactile sensor. Thus, the solution of the conflict of goals between the required deformability of the fingertip and the desired high initial sensitivity becomes feasible.

The generalized setup of artificial skin, depicted on the right, goes without a rigid base layer and solely consists of a mechanical damping layer and, on top, a stretchable tactile surface sensor. While the loss of dexterity of surgeons by the use of thin protective gloves is controversially debated e.g. in Webb and Pentlow [174] as well as in Sawyer and Bennett [131] no one would argue that the task of fastening a button of a shirt is not impaired by the use of thick, compliant gloves. The same holds true for the setup of robotic end effectors. The fingertip setup depicted in figure 3.22(a) consists of a rigid basis equipped with a tactile sensor that is then covered with a compliant surface layer. The dexterity on robotic manipulators and especially robotic hands depends on the sophistication of the actuated phalanges and the quality of the sensory feedback. For the application of sensorized robotic manipulators in tactile exploration poses additional requirements for the initial sensitivity of the artificial skin. The "classical" fingertip setup, figure 3.23(b) consists of a sensitive layer on the rigid bone of the robotic finger that is covered with a mechanical deformation layer. To enable the contribution of information derived from tactile sensors to a global 3D map of the environment the robotic manipulator may not alter the position of objects that are subject to tactile exploration. Sensor data fusion, e.g. of information derived from a vision system and data from a tactile sensor, for the creation of a global 3D map depends on the accuracy of the data fusion. If objects are moved during tactile exploration an update of the data derived from the vision system becomes inevitable. In order to avoid disturbing a scene of objects during tactile exploration a high initial sensitivity of the tactile sensors is required to minimize the interaction forces between robotic manipulator and explored object. In order to support grasp stability the contact area during grasps has to be increased and, if possible, a form closure has to be generated between robotic manipulator and grasped object. Therefore, the contact surface of the robotic manipulator has to be equipped with a compliant layer for grasp stabilization. To allow for the combination of the required high sensitivity and at the same time enable the introduction of a mechanical deformation layer for grasp sta-

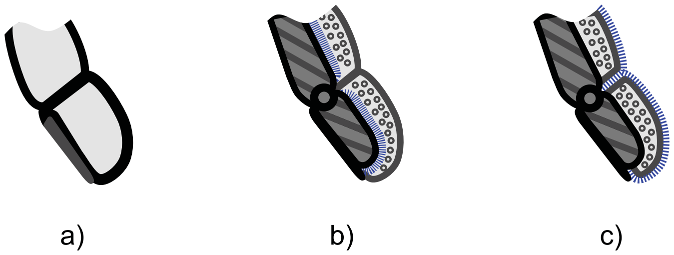


Figure 3.23: Configuration of extrinsic sensors for robotic fingertips a), cross section of the classical setup with rigid bone (ruled) sensitive layer on the bone surface and covering mechanical deformation layer b), artificial skin setup with rigid bone covered with mechanical deformation layer and superficial tactile sensor

bility enhancement an alternative fingertip configuration is proposed. The setup depicted in figure 3.23(c) consists of a rigid basis an internal compliant layer and a superficial tactile sensor. With respect to grasp stability Shimoga and Goldenberg [143] propose soft fingertips in order to enhance the ability of robotic fingers to securely grasp and manipulate objects with arbitrary surfaces. The authors propose a set of experiments and criteria for the evaluation of the fitness of different materials for the application as a basis for soft materials. The interested reader may be referred to the citations given in the paper, e.g. Akella and colleagues [1]. Curkosky and Wright [19] investigate various geometries for the design of robotic fingertips. The authors conclude, that compliant robotic fingertips based on elastomeric materials support grasp stability and enable the reduction of the required grip forces. Cutkosky et al. [18] investigate different polymer materials as a basis for the covering of robotic fingers. The authors attempt to answer the question "What is the best "skin" material for the contact areas of a robotic hand?". According to the authors,

> "From a design standpoint, most of these factors can be reduced to requirements in:
>
> - friction and adhesion under the range of expected gripping and handling conditions
> - mechanical properties such as resilience and elasticity
> - durability, resistance to abrasion and chemical attack
> - suitability for tactile sensing and compatibility with various tactile sensors."

Howe and Cutkosky [55] identify the importance of a soft layer for the design of robotic fingertips. The soft layer eases the difficulties of stable grasp force control and enables the mechanical decoupling of the sensor from vibrations induced from the robotic finger. The authors point out, that a soft layer enhances the conformability and thus enables increased contact surface areas and thus helps to improve grasp stability. In addition the authors identify the challenge of the fragility of the soft layer and recommend the design of the skin consisting of "a thin outer skin of relatively tough rubber and an inner layer of soft foam rubber".

Figure 3.24 depicts a grasping task with a "classical" fingertip setup. Already in figure 3.24(a) the surface of the robotic fingertips makes contact with the object. The covering mechanical deformation layer dissipates the energy transferred during the initial contact. Thus, the underlying internal tactile sensors are not capable to detect the initial contact between the surface of the robotic fingertip and the object. If the grasp force is increased, figure 3.24 (b), the covering layer is deformed

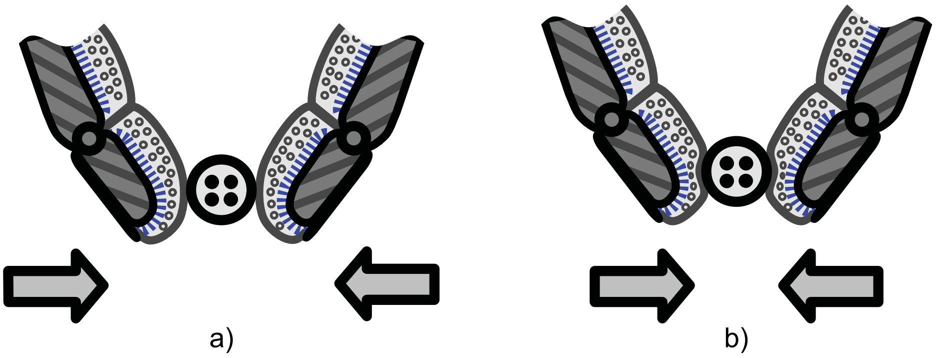


Figure 3.24: Grasping fine objects with "classical" robotic fingertips with an internal tactile sensor on the surface of the rigid skeletal structure of the robotic fingertip. The covering deformation layer prevents the detection of the initial contact between a small object (here a button) (a), only the increase of grasp force (b) results in a deformation of the covering layer that results in the detection of the contact between the robotic fingertip and the object.

and transmits the introduced indentation force to the underlying internal tactile sensors. Only at this time, the contact between the robotic fingertip and the object can be detected by the internal tactile sensors. In analogy to the mechanical damping layer for safe pHRI the compliant cover of robotic manipulators affects the derivation of information from tactile sensors. According to Shimojo [144] an elastic cover acts as a mechanical filter of the indentation force. Shimojo describes the distribution of point contacts at the surface of a polymer layer to the underlying sensing elements. Shimojo [144] investigates the spatial filtering effects of

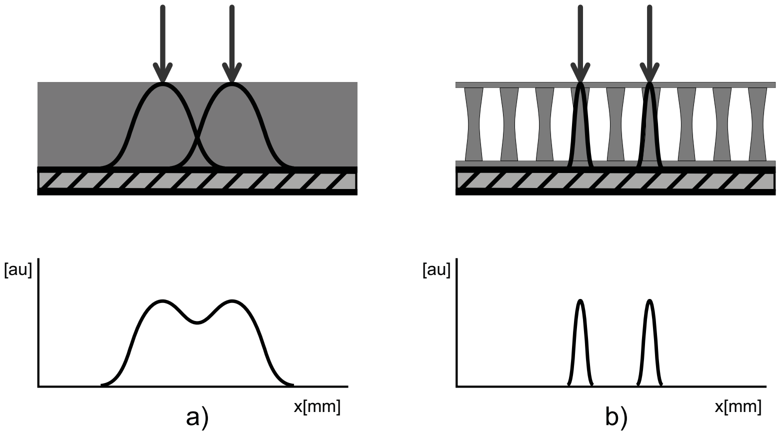


Figure 3.25: The proposed introduction of geometrically defined voids supports the desired increase of the spatial resolution and facilitates the discrimination of a two-point contact from a spatially distributed contact event

elastic cover layers on top of tactile sensors. The author concludes that even for a cover structure with a thickness of only $0.2mm$ the spatial filtering characteristics may not be neglected for the design of tactile sensors with a spatial resolution of $1mm$. Shimojo concludes, that the thickness and material properties of the covering material constrain the achievable spatial resolution of the underlying tactile sensor. Thus, the conflict of goals between the required deformation layer for grasp stability enhancement and the desired high spatial resolution may only be solved if the sensitive layer of the artificial skin is located on top of the deformation layer. Thus, the two-point threshold of the artificial skin becomes independent of the mechanical properties and the thickness of the deformation layer. Figure 3.25 depicts the implication of the structure of the covering layer. The application of a solid polymer volume, figure 3.25(a) results in the lateral distribution of the indentation force. For a close two-point indentation the mechanical covering structure distributes the point loads laterally. Thus, the capability of the underlying tactile sensors to discriminate a distributed contact event from a two-point indentation event is restricted. Therefore, a structuring of the covering layer is proposed, see figure 3.25(b). The introduced voids in the covering structure prevent the lateral distribution of the indentation forces. Thus, the two individual point loads can be reliably discriminated from a spatially distributed contact event. If the sensitive layer is located on top of the deformation layer the mechanical energy introduced by a grasped object can be directly applied for the deformation of the surface sensor and thus be utilized for the transduction into a measurable domain, figure 3.26 (a). Hence the proposed setup enables a high initial sensitivity and thus enables the solution of the goal conflict between required deformability and high initial sensitivity. An increase of grasp force, figure 3.26, results in a further deformation of the superficial tactile sensor and thus enables the activation of additional taxels. This results in an increase of information that can be derived from the tactile surface sensor and thus allows e.g. for the determination of a stable grasp configuration. The location of the sensitive layer with respect to the overall covering of the rigid structure of a robotic fingertip is important for the dexterous manipulation of fine objects. Therefore, one may draw the following general conclusion:

In order to enhance the dexterity of robotic manipulators a compliant base layer and tactile surface sensors with high spatial resolution are desirable. And, more general: The distance of the tactile elements from the surface should be minimized. The proposed setup of an underlying deformation layer and a superficial tactile sensing layer requires a completely stretchable design of the sensitive area of the surface sensor in order to allow the sensitive layer to conform the the surface of an indenting object and thus to support the grasp stability. Moreover, the surface

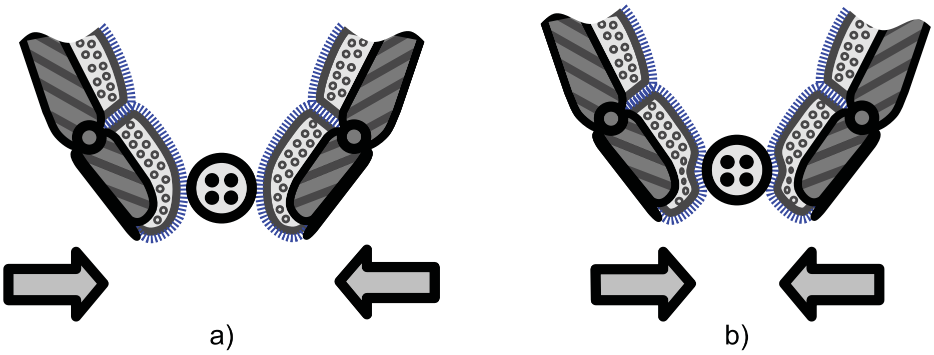


Figure 3.26: Robotic fingertips that are designed according to the design paradigms derived in section 3.2.7 consist of an internal deformation layer and a superficial tactile sensor. The superficial tactile sensor requires only a small contact force in order to generate a measurable sensor output and thus enables the detection of the initial contact even for small objects (a). An increase of grasp force results in additional taxels to be activated and generates additional information regarding the contact area (b).

properties of the sensing layer contribute to the friction properties of the resulting artificial skin. Thus, the development of the structure and the material of the surface layer of the artificial skin has to enable friction enhancement in order to support the dexterity of the underlying robotic finger.

Whole-body cover for physical human robot interaction

While the motivation for the design of a touch sensitive cover for the entire surface of a robotic system is different, the principles applied for the design of a fingertip setup are equally applicable for the design of an artificial skin as a whole-body cover for robotic systems. The motivation for an artificial skin results from the requirements of a safe and intuitive safe physical human robot interaction (pHRI). Here, the conflict of goals arises from the desired combination of a collision tolerant design and a required high initial sensitivity in order to allow for the discrimination between a collision and an intended physical interaction. Furthermore, a high initial sensitivity of the artificial skin is required for an intuitive pHRI. An intuitive pHRI is required in order to enable an increase in productivity arising from the direct physical interaction of humans and robots in an industrial assembly scenario, where humans and robots e.g. jointly assemble an automobile. Here, the robot carries the weight of the pre-assemble components for the equipment of the car interior. In order to successfully introduce and fixate the components inside the car body, human and robotic colleague have to physically interact. Besides safety issues the intuitive control of the robotic manipulator by the human user is essential for a time saving interaction. Standardized teach-in and repeat control for the trajectories of the robot manipulator will not enable the exploitation of the potential of the human-robot co-operation. Therefore, entirely new interaction and communication procedures have to be implemented. Recent research by Haddadin et al. [48] shows the potential of a co-operation based on the physical interaction between human user and the entire structure of the robot manipulator. Based on the information from the intrinsic sensors of a DLR lightweight robot (LWR III) the human user can alter the trajectory of the manipulator or change the reaction strategy in case of a collision. While intrinsic sensor provide accurate information regarding torque disturbances and thus allow for the calculation of the resulting interaction or collision force vector, no information regarding the spatial distribution of the physical stimulus can be provided if multiple simultaneous points of contact exist. Therefore, the information stemming from the intrinsic sensors can be optimally supplemented by information from spatially distributed tactile sensors on the surface of the robotic manipulator. Requirements for a successful application of tactile sensors as input channel for a HMI are a high sensitivity and the robustness of the sensor hardware. The "classical" tactile sensor configuration, figure 3.27(a), consists of a single, mechanically compliant layer functioning as transduction medium that enables the required deformation and contributes to the thermal management of the underlying robotic system. This setup necessitates a number of tradeoffs, e.g. the initial sensitivity conflict the robustness of the sensor. In addition, the

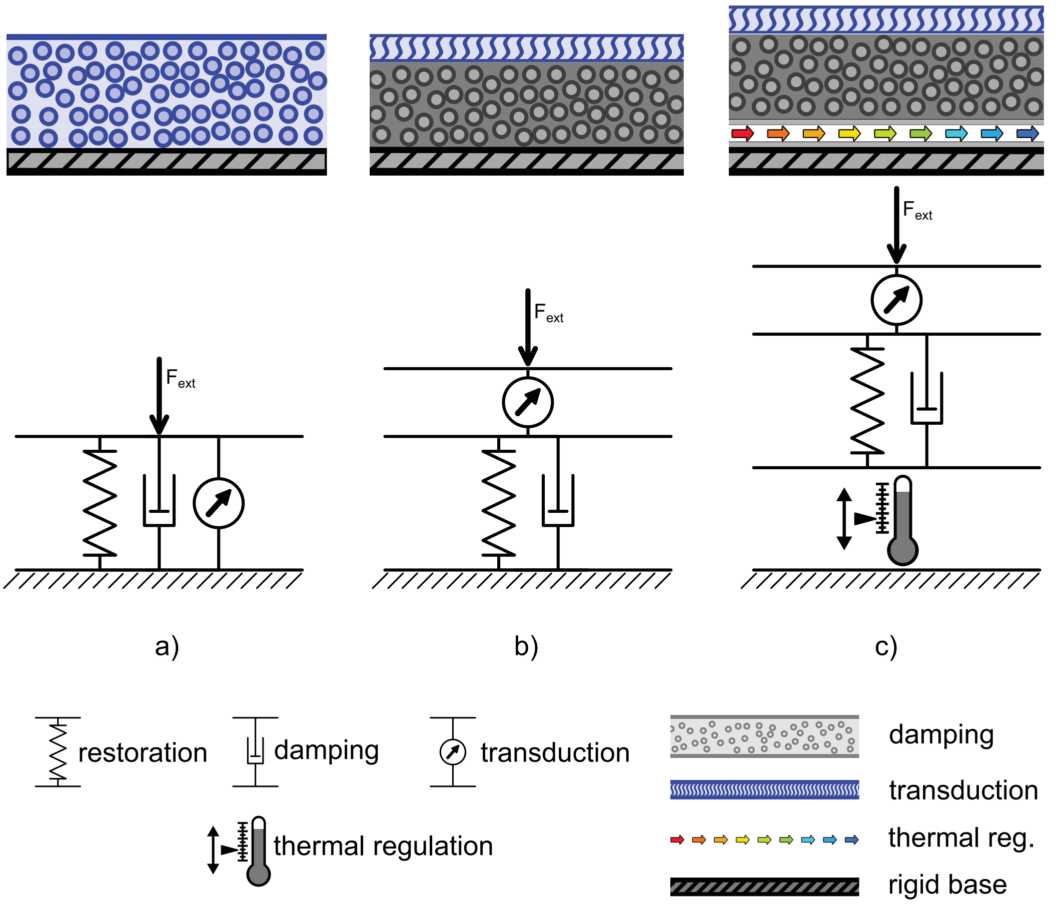


Figure 3.27: The tactile sensor setup, based on a uniform polymer layer providing mechanical damping and transduction properties (a). This setup results in a tradeoff between mechanical properties and transduction properties. The functional partitioning allows for the development of a setup consisting of a superficial transduction layer and an underlying mechanical damping layer (b). The long term goal is the design of a multi-functional artificial skin based on dedicated functional layers for transduction, damping and thermoregulation (c).

required damping properties contradict a fast restoration of the sensor after the release of an external stimulus. Figure 3.27(b) depicts the setup proposed within this thesis, the combination of two dedicated functional layers, a superficial sensing layer and an underlying mechanical deformation/damping layer. On the one hand, this setup results in the reduction of the required tradeoffs, as e.g. the mechanical damping properties can be optimized without affecting the sensory capabilities. On the other hand, this setup requires the development of a superficial sensing layer that can be operated on top of a compliant mechanical damping layer.
Figure 3.27(c) depicts the long term goal, an artificial skin setup consisting of a superficial sensing layer, a mechanical damping layer and an underlying thermal management layer that contributes to the dissipation of the excess thermal energy from the robotic system.

Recent studies of Haddadin and colleagues, e.g. [116] have shown that for pHRI a compliant damping layer on the cover structure of a robotic system can help to prevent laceration and soft tissue damage. If an object comes into contact with the surface the damping layer will shun from the load and allow the object to indent the surface. Thus, high local pressures are distributed to a larger surface and the severeness of the collision can be reduced. Covering a robotic structure, e.g. a robotic forearm, see figure 3.28(a) with a combined transduction and damping layer, figure 3.28(b) results in a goal conflict between the transduction properties and the mechanical damping properties. During the development this setup always requires tradeoffs between transduction properties and mechanical damping properties. Therefore, an alternative layer setup is proposed for an artificial skin. Figure

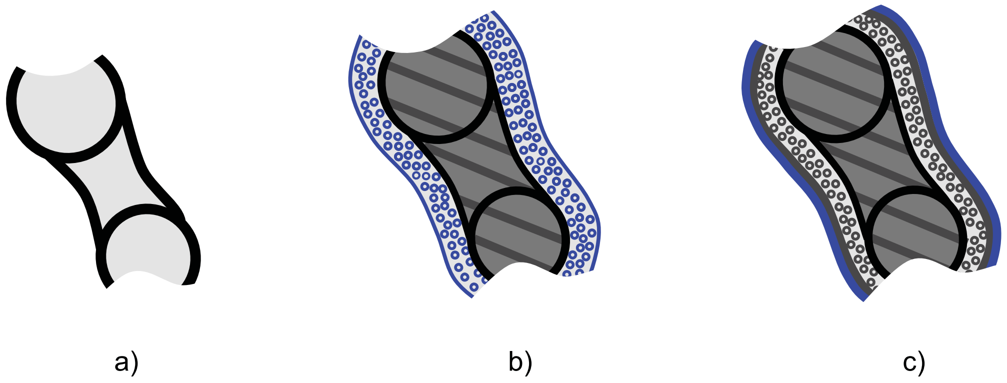


Figure 3.28: Covering a robotic structure (a) with a single layer, acting as both, as transduction medium and mechanical damping layer (b) results in mechanically robust design but prevents a high initial sensitivity. Locating the sensitive layer of a whole body cover for a robotic system on top of a separate mechanical damping layer results in a high initial sensitivity but requires a stretchable design of the sensitive layer, (c).

3.28(c) depicts the setup consisting of an internal mechanical damping layer and a superficial sensing layer. This setup allows to the dedicated material selection and optimization of the properties of the individual layers. With respect to safety, combining transduction and mechanical damping in a single layer as a cover for a robotic system poses three general problems: Firstly, as intended for passive collision severeness reduction, the deformation of the combined layer dissipates kinetic energy, see figure 3.29(a) and thus helps to increase the safety of pHRI. While beneficial for the passive safety properties of the robotic system, the mechanical damping properties of the combined sensing/deformation layer limit the initial sensitivity and thus affects the ability of the robotic system to actively react to mechanical stimuli. Secondly, if transduction and damping properties have to be combined, sensor provides the information of an occurring impact only after the combined layer has been deformed, see figure 3.29(b). The robot control system can thus start to react in order to counter the effects of the impact after the deformation of the damping layer. Hence it is not possible to utilize the combination of the passive damping layer and active collision reaction strategies based on tactile information and as a redundant safety feature. The drawbacks of a covering mechanical damping layer can be avoided by locating specialized tactile surface sensors on top of a dedicated mechanical damping layer. Based on the information from tactile surface sensors active collision reaction strategies can be implemented in the robot control. In combination with the passive mechanical damping layer for the reduction of collision severeness redundant safety features for pHRI can be

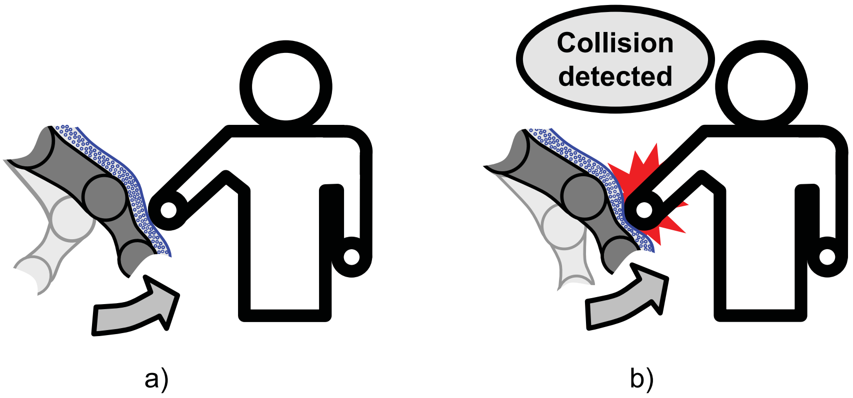


Figure 3.29: The "classical" setup of combination of tactile sensing and mechanical damping in a single layer (a) enables the detection of a collision event only after the entire layer has been deformed. Thus, the information regarding the occurrence of the collision is available only after the passive collision reaction strategies have been deployed (b). The time span for the active collision severeness reduction strategies to take effect has to be bridged by the deformation properties of the indenting object. In case of a rigid object or a vulnerable portion of the body of the interacting human an injury or the mechanical damage of the robotic system can not be avoided for high velocities of the robotic system.

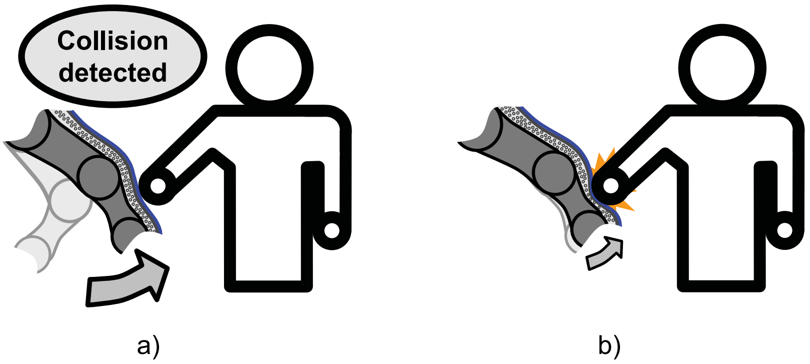


Figure 3.30: The introduction of tactile surface sensors on top of a mechanical damping layer enables the instantaneous detection of a collision during pHRI, (a). The information regarding the detected collision is provided to the control system in order to trigger active collision severeness reduction strategies. The time span required for the control system to react and the initiated collision reaction strategies to take effect can be bridged by the passive collision severeness reduction properties of the underlying mechanical damping layer. Therefore, the design of the passive mechanical damping layer has to account for the reaction time of the artificial skin and vice versa. At the instant of time when the mechanical damping layer is fully compressed (b), the velocity of the robotic system has already been reduced by the active collision reaction strategies. Thus, the residual relative velocity does no longer endanger neither the interacting human nor the robotic system. Designed accordingly, the combination of active collision detection/reaction and passive collision severeness reduction properties enables the cushioning of unintended collisions and thus contributes to an enhanced safety during pHRI.

created. In case of a collision between the robot and a rigid object the tactile sensor located on the surface of the damping layer can detect the impact quasi instantaneously, see figure 3.30(a). While the underlying damping layer is being deformed by the impacting object, the control system can react to the impact according to the chosen strategy and thus reduce the kinetic energy dissipated during the collision, see figure 3.30(b). In addition the design of the damping layer may help to deflect the impact from delicate areas on the robot's outer structure towards areas more capable to withstand the effects of an impact. Locating the touch sensitive layer on top of a damping or deformation layer introduces a series of additional challenges for the design and manufacturing of these sensors. The salient surface sensor has to exhibit a deformability exceeding the deformability of the underlying damping layer to prevent mechanical destruction of the sensor in case of a collision. This required high deformation of the surface sensor prevents the application of rigid elements like standard resistors or metal based circuit tracks. Thus, the application of standard flexible printed circuit boards for the design of the sensitive area of a tactile surface sensor is not possible. While posing additional challenges for the design and manufacturing of the sensor hardware, the introduction of a mechanical damping layer below the sensitive layer allows for the design of a redundantly safe cover for the robot.

3.2.8 Discussion

The system design of artificial skin according to the proposed operation–oriented approach enables an artificial skin setup that allows for the solution of the most prominent conflict of goals between the required mechanical robustness and desired high initial sensitivity. The proposed scalable design accounts for the desired spatial and functional integration into a robotic system and thus renders the application of artificial skin on a robotic system possible. The pursued approach allows for the implementation of robotic fingertips with high spatial resolution while at the same time enabling the design of a touch sensitive covering for the large surface areas of an entire robotic system. The proposed strategy of the sequential increase of the information content is based on existing knowledge derived from the analysis of the literature from the last thirty years. The approach allows for the reduction of the acquired amount of data and thus helps to reduce the reaction time of the artificial skin in case of a contact event. Therefore, the provision of tactile information at update rates suitable for robotic manipulation and collision reaction strategies is enabled. The functional partitioning of the artificial skin into specialized layers allows for the independent optimization of the functional components and thus enables the solution of the conflicts of goals. Following the domain specific design proposed in VDI 2206 [169] in the next section specialized functional components for a multi-functional artificial skin are designed. Applying the integrative design of functional components and the required manufacturing processes a toolbox for the development of an adaptable artificial skin is proposed. Therefore, the artificial skin is subdivided into the following functional components: Sensing elements, basic mechanical structure and physical interface to the target system.

3.3 Adjustable functional components

In the following section concepts for the functional components of an artificial skin for robotic systems are derived. According to the proposed partitioning of the functional range of an artificial skin the components are subsequently developed in order to account for the cross-correlation of requirements between the individual functional components. The development of a set of adjustable sensing elements for the acquisition of the most prominent modalities of a physical stimulus forms the basis of a toolbox for the development of an artificial skin that can be adapted to the requirements of the application site on the robotic system. Subsequently, a concept for the basic mechanical structure providing the spatial fixation and required restoration forces for the sensing elements is developed. Finally a solution for the physical hard-soft interface between the sensing elements and the readout electronics is presented.

3.3.1 Sensing elements

Within the following section solutions for the acquisition of the following stimulus modalities are derived:

- Normal force
- Shear force
- Slip detection

The development is focussed on the integrative design of the functional components and the required manufacturing processes and applied materials. Therefore, the underlying manufacturing processes are designed prior to the definition of the requirements for the material properties, thus a materials selection enabling the application of the required manufacturing processes becomes feasible. The focus of this approach is to enable the multi-modal scalability trough the introduction of adjustable artificial skin components. For the development of dedicated sensing elements the expected stimulus resulting from a physical contact between an object and the artificial skin of a robotic system can be divided into a subset of modalities. Figure 3.31 depicts the modalities of a mechanical stimulus, it consists of normal force (a), shear force (b) or their combination (c). Selective normal or tangential indentations are special cases, in general the force vector consists of a combination of normal and tangential indentation force. If the friction is not sufficient to transmit the tangential component of the indentation force, stick slip effects result in a sliding of the indenting object over the sensor surface. The result is a vibration of

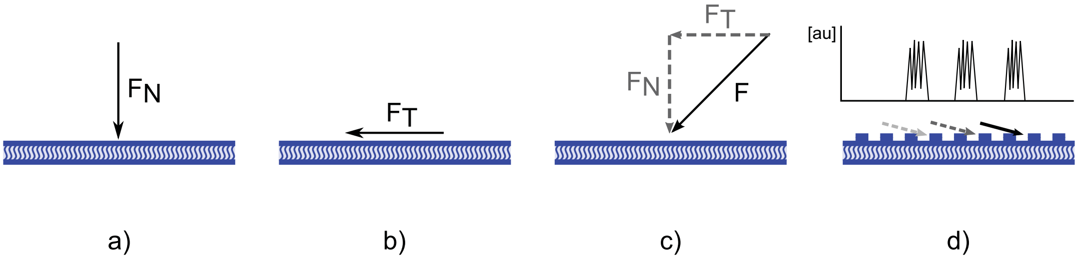


Figure 3.31: The force component of the stimulus can be classified as normal indentation force a), tangential indentation force b), and combined indentation force c), which contains components in normal and tangential direction. In addition, a tangential relative movement between the surface of the artificial skin and an object in physical contact results in vibrations that have to be acquired by the artificial skin d), in order to enable the detection of slip between the surface of the artificial skin and an object, e.g. for the autonomous grasp force adjustment during robotic manipulation.

the sensor surface. This vibration can be acquired by high frequency redout of the normal force sensing elements or globally by a dedicated vibration sensing element. Figure 3.31(d), depicts the vibration induced by relative movement between indenting object and the surface of the tactile sensor. Tactile sensors can be developed utilizing a multitude of transduction principles. The approaches are mostly based on the acquisition of changes in:

- Electrical resistivity
- Electrical capacitance
- Light intensity or frequency
- Magnetic field
- Ultrasonic wave intensity

The different transduction principles and their advantages and disadvantages for the application in tactile sensing for robotics are reviewed e.g. in Nicholls [103]. The fitness of the individual transduction principles for the application in multi-fingered grippers is analyzed e.g. by Weiß [176]. Weiß concludes that tactile sensors based on the measurement of electrical resistivity in polymers offer the best match to the requirements of robotic grippers. Differentiated according to the transduced stimulus modality various transduction principles are reviewed by Cutkosky et al. in their chapter in [146]. Nicholls [103] presents a list of advantages and disadvantages of different transduction principles. The author states, that:

> "A wide range of transduction methods have been used, from techniques based on measuring change in resistance to photoelastic methods. No

> single technology has proved to be suitable for all applications, or to satisfy all of the design criteria specified for ’usable sensors’".

Therefore, a set of dedicated sensing elements is developed for the different modalities of an external stimulus. For each modality a suitable transduction principle is proposed. Below, sensing elements for the acquisition of normal force, shear force and vibration are designed.

Normal force acquisition

The functionality of the sensory elements for the acquisition of normal forces can be abstracted as the transduction of mechanical input energy of a stimulus in normal direction related to the surface of the sensor into an electrically measurable quantity. This can be achieved by various transduction principles. Following the common transduction principles are evaluated with the focus on the compatibility of the approaches with the proposed design paradigms. According to Cutkosky et al. [146] P.457, normal pressure is commonly transduced by arrays of piezoresistors, capacitors, micro electro mechanical systems (MEMS) or through a camera based tracking of optical markers. While commonly utilized in the context of tactile sensors, the original definition of piezo-resistivity, (e.g. described in Smith [151]) refers to changes in electrical resistivity within mechanically loaded semiconductor structures. Most of the polymers that are applied for the development of tactile sensors exhibit amorphous characteristics. Therefore, the utilization of "piezo" in this context is somewhat misleading. Nonetheless, the effect of a decreasing electrical resistivity in mechanically loaded polymers – in this thesis referred to as mechano-resistive characteristics – forms the basis for the development of tactile sensor arrays. Cutkoksy et al. present a detailed assessment of the advantages and disadvantages of the different transduction principles in their chapter in [146]. The authors list simple design and signal conditioning and suitability for mass production as advantages for tactile sensors based on resistive arrays. While temperature dependency, drift and hysteresis as well as frailty are considered disadvantages of resistive array sensors. Following the transduction of normal forces based on changes in electrical capacitance and resistivity are outlined.

Capacitance based approaches With respect to tactile sensors based on changes in capacitance Nicholls [103] state:

> "Capacitance sensors show some promise. The noise problem seems to be partly soluble, and the sensors give wide dynamic range and are robust. However, capacitance decreases with reduced physical tactel size

> and so stray signals will influence the sensor output for very small sites."

For the robotic finger of the Stanford/JPL hand Fearing [32, 33] develop a capacitance based tactile sensor with 8×8 taxels. The taxels are arranged around a cylinder along the axis of the finger. In order to acquire the indentation forces that are exerted to the hemispherical fingertip a ring shaped electrode is arranged perpendicular to the finger axis below the hemispherical rubber finger tip. An example for a sensor based on the change of the dielectric medium is presented by Cannata et al. [12]. The proposed approach is based on the acquisition of the changes of the capacitance between the sensor and e.g. a human finger that approaches the sensor. The authors point out, that this effect is limited to the detection of electrically conductive objects and therefore propose the application of a deformable polymer based reference top electrode. Figure 3.32 depicts the general transduction principle. A change in the distance between the plates of a capacitor results in a change in capacitance according to:

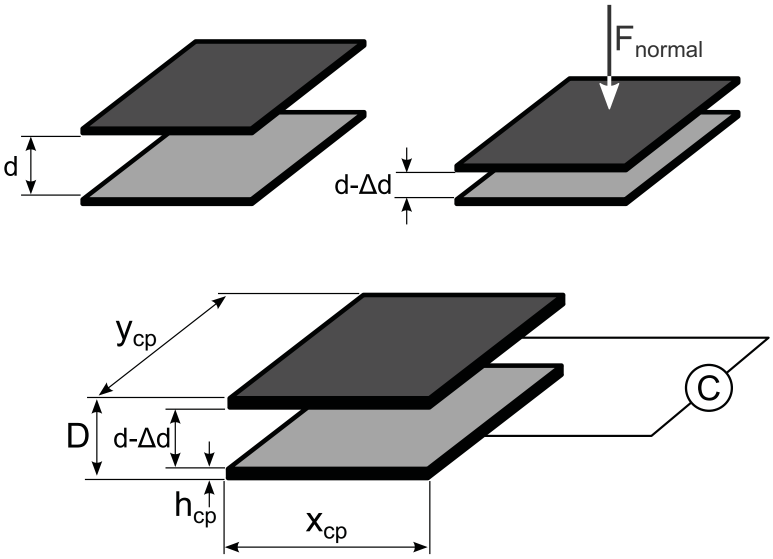


Figure 3.32: Tactile sensors based on the acquisition of changes in electrical capacity often make use of changes in electrical capacitance resulting from a deviation of the upper electrode of the capacitor. The displacement of the upper electrode results in a deformation of the dielectric medium between the capacitor electrodes. Thus, the measurable electrical capacitance changes, depending on the external mechanical stimulus.

$$C(\Delta\ d) = \frac{\varepsilon_0 \varepsilon_r \cdot A}{d - \Delta\ d} \tag{3.3}$$

Where $\varepsilon_0 \varepsilon_r$ represents the dielectric properties of the material separating the electrodes of the capacitor, d the distance between the electrodes without mechanical load and $\Delta\ d$ the change in distance induced by the mechanical load. According to Schrüfer [138] the sensitivity of a transducer based on the change of the distance between two plates of a capacitor is defined as:

$$E = \frac{dC}{\Delta d} = -\frac{\varepsilon_0 \varepsilon_r \cdot A}{d^2} = -\frac{C}{d} \tag{3.4}$$

Schrüfer states, that the sensitivity is high for small distances between the plates of the capacitor:

$$\frac{dC}{C} = -\frac{\Delta d}{d} \tag{3.5}$$

The mechanical properties of the material separating the electrodes defines the transfer function

$$C = f(\Delta\ d) = f(\Delta\ P) \tag{3.6}$$

Where P is the pressure resulting from a normal indentation force applied to the surface area A of the capacitor. The pressure P on the capacitor is defined by:

$$P = \frac{F}{A} \tag{3.7}$$

The measurement range depends on the relation of:

$$\frac{C}{C_0} = f(\frac{d}{d - \Delta d}) = f(\frac{1}{1 - \frac{\Delta d}{d}}) \tag{3.8}$$

The desired scalability poses a series of challenges for the readout electronics of a capacitance based tactile sensor array. For tactile sensors with a high spatial resolution the absolute capacitance becomes very small as it depends on the surface area of the capacitor according to:

$$C_0 = f(A) \tag{3.9}$$

If air is utilized as dielectric medium between the electrodes the resulting absolute capacitance of the tactile elements is very small and thus requires a very sophisticated readout electronics and rigorous EMI-shielding. Mannsfeld et al. [94] present a highly sensitive tactile sensor matrix based on the acquisition of changes in capacitance. The applied process enables the introduction of geometrically defined void into the senor surface. In case of a mechanical compression the polymer material can shun from the load and fill the introduced voids. According to the authors thus mechanical creep phenomena are reduced enabling fast restoration times after an external load is removed. Although the applied materials do not enable the stretching of the resulting sensor, the approach of the introduction of geometrically defined voids instead of applying soft or porous polymer materials is beneficial for the desired increase of the sensitivity of artificial skin sensors. Lee et al. [83] present a bendable three axis tactile sensor with $2mm$ spatial resolution. Small indentation forces in the order of Millinewtons result in small displacement of the electrodes of the capacitor (Δd in the order of μm). The resulting relative change in capacitance is ($C/C_0 = 1.5$). The absolute capacitance ranges in the order of hundreds of femto-Farad. The authors state, that the full scale range of the sensor is $20\ mN$. For the application, e.g. in a robotic gripper, a high dynamic range is required. In order to enable an increased measurement range, the variable distance between the electrodes (currently $6\ \mu m$) would have to be increased. According to the authors the theoretical capacitance of the sensing elements is $172\ fF$. The absolute change in capacitance is thus $\Delta C_{abs} = 1.5{\cdot}172fF{-}172fF = 86fF$ For a resolution of $8bit$ an absolute change in capacitance of $0.336fF$ has to be acquired by the readout electronics. While the challenge of the acquisition of small absolute changes in capacitance can be met by a careful design of the readout electronics, the authors omit the effects of electromagnetic influence (EMI) to the sensor setup. The EMI-shielding of sensor setups based on the acquisition of capacitance is crucial for the desired integration into a robotic system. For the application on robotic systems, e.g. the surface of the torso of a humanoid robotic system, tactile sensors based on the measurement of changes in electrical capacitance are impeded by the required elastic deformability. The readout electronics for capacitance measurement require electrically highly conductive electrodes for the plates capacitors. The desired all-polymer design of the sensitive area of the tactile sensor prevents the application of rigid or flexible metal-based electrodes for the capacitors. The comparatively low electrical conductivity of capacitor plates based on standard particle filled polymers constrains the scanning rate of the resulting sensor system. Given good EMI shielding and an adequate electrical conductivity of the polymer based electrodes, an approach towards highly sensitive tactile sensors based on the acquisition of changes in electrical capacitance is promising as highly integrated readout chips are available of the shelf. An approach towards EMI-shielding based on carbon black filled silicones is presented by Barba et al. [5]. The authors proposed a predictive model for the design of EMI shielding. Based on this or a similar approach a stretchable EMI shielding layer for a capacitance based sensitive layer of an artificial skin might be feasible. Therefore, the acquisition of changes in capacitance is envisaged in the design of the tactile surface sensors.

Resistivity based approaches One of the most common transduction principles is the acquisition of changes in electrical resistivity. Two principle approaches are pursued. The acquisition of changes in the volume resistivity of a polymer material, see figure 3.33(a) and the acquisition of changes in the transition resistivity between two electrically conductive volumes, see figure 3.33(b). Already in 1993 Nicholls [103] describes the two basic transduction principles. Nicholls concludes, that:

> "Approaches based on measuring resistance have probably received the most amount of attention in tactile sensing, and several designs have been quite successful. A wide dynamic range can be attained with considerable durability. Hysteresis and creep are present in most designs, probably because of the reliance on elastomers."

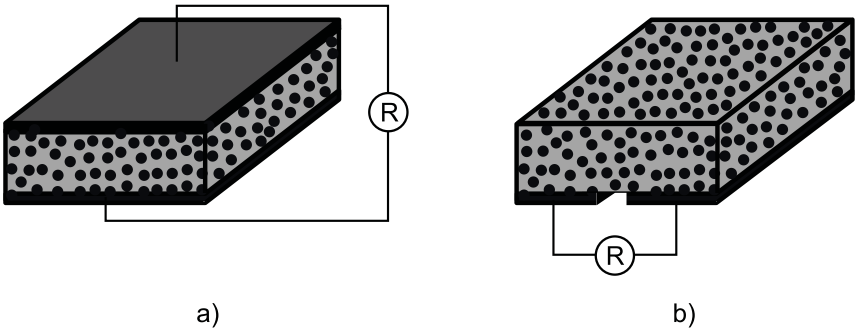


Figure 3.33: The principle setup for tactile sensors is often based on the acquisition of changes in electrical volume resistivity, (a). The deformation of the mechano-resistive medium between the contacting electrodes results in a change in electrical volume resistivity. The measurable electrical resistivity changes, depending on the applied external normal force. This principle is applied e.g. by Duchaine et al. [27] Alternatively the transition resistivity between an electrically conductive polymer and metal based contacting electrodes can be acquired, (b). For planar contacting surfaces between the two volumes, according to Weiß [176], the transition resistivity depends primarily of the microscopic surface structure of the polymer material.

Figure 3.34 depicts the transduction principle of mechano-resistive tactile sensors based on changes in electrical volume resistivity. An approach based on volume conductivity is applied e.g. by Duchaine et al. [27]. The authors present a tactile sensor setup based on a pressure sensitive rubber layer that is electrically contacted by two orthogonal sets of brass electrodes on the top and bottom of the pressure sensitive rubber layer. The authors report a pressure threshold of approximately $100kPa$ and a quasi binary sensor output. While sufficient for the detection of collisions, a binary transduction principle is appropriate as a means for an intuitive pHRI and thus is not suitable for the integration into a robotic system. An alternative approach that avoids the introduction of metal based readout electrodes is presented by Fritzsche et al. [35]. The authors present a touch sensitive cover for industrial robots based on the evaluation of pressure induced changes in the electrical conductivity of a polymer foam. The top and bottom contacting electrodes are designed based on electrically conductive textile. Thus, the presented sensor setup enables the required deformability to be operated on top of a mechanical damping layer. External indentation forces compress the electrically conductive polymer foam, resulting in a measurable increase of electrical volume conductivity of the polymer foam. As a result of the applied configuration the polymer foam acts as transduction medium and provides the restoration forces enabling the recovery of the tactile sensor after the release of an external indentation force. Thus, there will always be a tradeoff between the desired electrical transduction properties and the required mechanical deformation properties. While being well suited for the targeted safety enhancement for industrial robotic systems the pursued approach prevents the application of the sensor system if the transmission of mechanical energy, e.g. for robotic object manipulation is desired. This limitation results from the mechanical properties of the applied polymer foam, being inappropriate to transmit shear forces required for robotic object manipulation. The second approach is based on the acquisition of changes in electrical transfer resistivity between two volumes. Most commonly a deformable polymer volume is combined with a metal

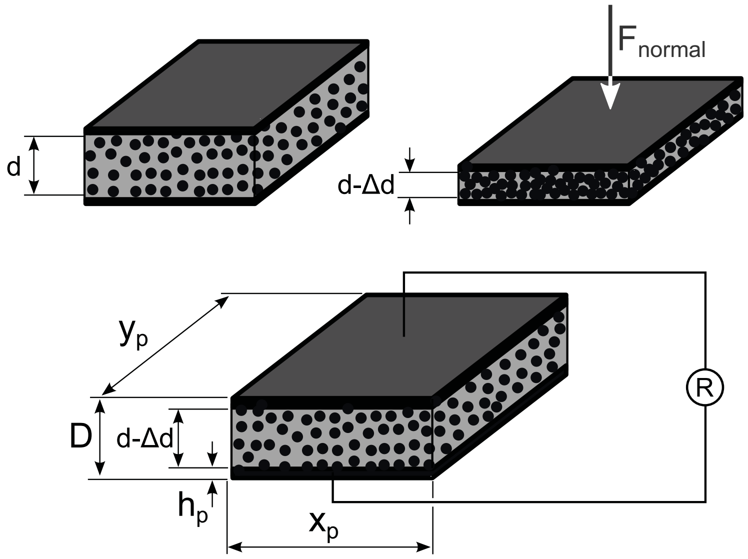


Figure 3.34: A deformation of the mechano-resistive medium between the contacting electrodes results in a change in electrical volume resistivity of the polymer material. The measurable electrical resistivity depends on the external mechanical load.

based electrode. In the extensive study of Weiss [176] with a focus on transition resistivity acquisition revealed, that the variation of the transfer resistivity between a planar deformable polymer and an equally planar metal based contacting electrode is primarily based on the deformation of the microscopic surface structure of the polymer material as a result of an external indentation force. An approach based on a combined acquisition of volume and transfer resistivity is presented by Schostek [136]. The proposed transduction principle is applied in a palpation device for minimally invasive surgery. The reported high sensitivity and the wide dynamic range suggest the application of a transduction principle based on the acquisition of transfer resistivity.

Concept The above presented examples show that both transduction principles, the acquisition of changes in electrical capacitance as well as the acquisition of changes in electrical resistivity are equally suited for the design of taxels for the acquisition of normal forces. Both principles are prone to advantages and disadvantages, see e.g. Cutkosky et al. in [146]. Therefore, no disguised attempt to introduce essentially arbitrary assessment criteria to favor one of the two transduction principles is made. Solely, the simplicity of the required readout electronics and the somewhat less demanding EMI shielding led to the decision to opt for a transduction based on changes in electrical resistivity. Thus, within this thesis exemplarily a concept for the design of taxels for the acquisition of normal forces based on changes in electrical resistivity is presented. The individual taxels have to be arranged in order to form a spatially distributed touch sensitive area. The challenge of the integration into a robotic system requires a compromise between the quality of the measurement of the individual taxels and the number of the required readout wires. According to the discussion in section 3.2.6 the arrangement of the individual taxels in a matrix setup combines the advantages of a satisfying quality of the measurement with the required spatial resolution. In addition, a matrix arrangement of taxels reduces the complexity of the inverse computation of the location of the contact. Therefore, the transduction of normal forces is based on the application of mechano-resistive taxels, , see figure 3.35(b) in an array configuration, see figure 3.35(a). Furthermore, a matrix arrangement enables the desired scalability of the artificial skin and thus promotes the introduction of artificial skin as a whole-body cover for entire robotic systems.

To further a high sensitivity of the resulting sensor the deformed material volume is reduced by the application of discrete, spatially separated taxels instead of a solid polymer volume. In the review of Nicholls [103] various transduction principles and sensor setups are discussed. The following quotation of Nicholls describes a sensor

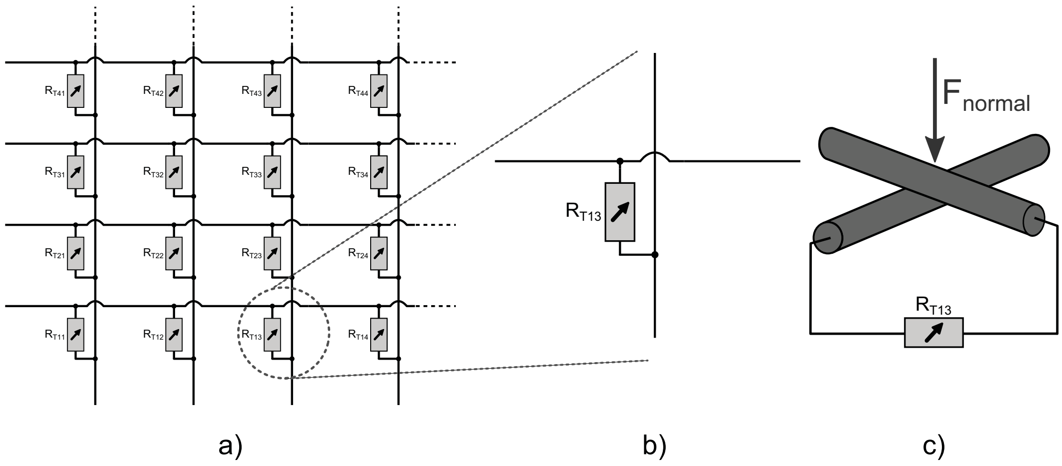


Figure 3.35: The basic setup of the normal force acquisition is based on an array of mechano-resistive taxels, (a). Readout wires are arranged in two orthogonal layers with a mechano-resistive taxel at each crossing point. Ideally, the variable resistivity is independent of the resistivity of the readout wires, (b). For the application in an artificial skin the readout wires are designed as polymer based circuit tracks (PBCT), (c).

setup based on the orthogonal arrangement of carbon fibers. Nicholls states, that:

> "Carbon fibres have been used in several tactile sensor designs [...].Carbon fibres are filaments of carbon created by baking unspun textile yarns, and are cylindrical in cross-section. When two fibres rest in contact with one another, the area of contact is very small, but when they are pushed together, the contact area increases, thereby increasing the electrical conductivity at the junction."

According to the proposed design paradigms no rigid element can be introduced into the mechanically loaded sensing area, thus the application of carbon fibers is not feasible for stretchable artificial skin. Therefore, the basic idea of the application of two orthogonal intersecting cylindrical volumes for the design of a mechano-resistive sensing array is adapted. The proposed carbon fibers are replaced by electrically conductive polymer based electrodes. The transduction of external mechanical stimuli in the individual taxels is based on the mechanically induced alternation of the contact surface area between two intersecting electrodes. Figure 3.35(c) depicts the principle setup. Jacobsen et al. [57] identify the interface between sensor and readout wires as central challenge for the successful integration of tactile sensors into robotic systems. The authors state, that:

> "Connections to the sensor should be minimized to reduce the probability of site failure due to wire breakage, and conductors must exhibit reasonable lifetimes under conditions of constant flexing."

This statement supports the proposed all-polymer design paradigm and the resulting principle of the exclusion of the mechanical hard-soft interface form the mechanically loaded area. In order to enhance the mechanical robustness of an artificial skin the number of interfaces is reduced through the merging of contacting electrodes and readout wires. The functionality of the contacting electrodes, to provide an mechanically induced change of contact surface, is combined with the contacting functionality of the readout wires. The resulting structure is referred to a polymer based circuit track (PBCT). Figure 3.36(a) depicts the principle of an individual taxel based on two crossing PBCT. The ideal properties of an array of mechano-resistive taxels can not be achieved if electrically conductive polymers are applied instead of metal based readout wires. The measurable electrical resistivity of an individual taxel consists of the combination of volume resistivity and transition resistivity at the crossing point, see figure 3.36(b). Thus, a cross-correlation between the individual taxels of a matrix configuration, see figure 3.36(c) is observed. In Schnös [135] the cross-correlation of an array of taxels based on PBCT is

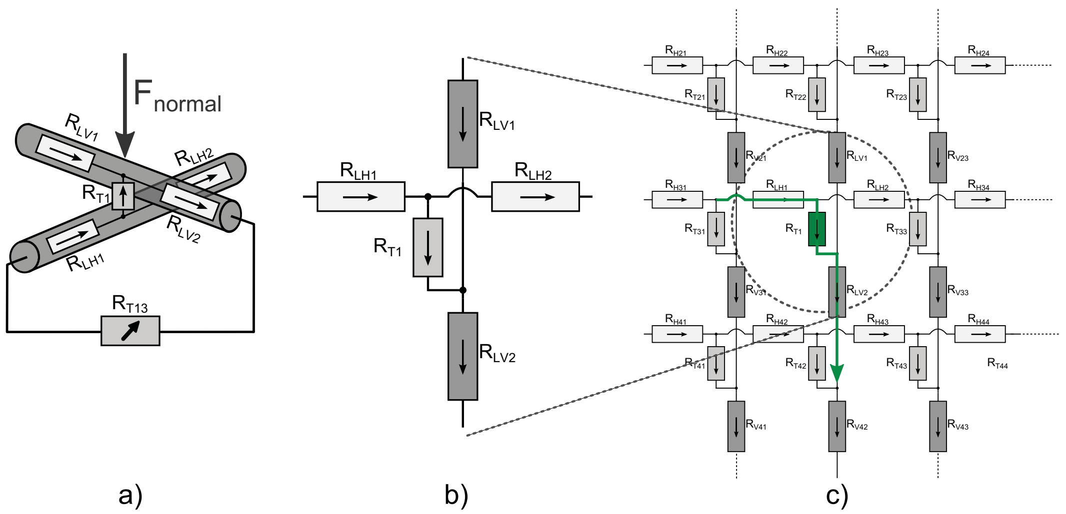


Figure 3.36: Real PBCT exhibit The acquisition of the transition resistivity is affected by the volume resistivity of the PBCT (a). Subfigure (b) depicts the equivalent circuit diagram for a normal force acquisition taxel based on two intersecting PBCT with non-negligible electrical volume resistivity. Subfigure (c) exemplifies the electrical equivalent circuit diagram for a matrix configuration of multiple normal force acquisition taxels.

analyzed and a strategy for the minimization of this systematic measurement error is proposed.

Following, possible manufacturing technologies for the implementation of PBCT are derived. In accordance to the proposed partitioning of functional range of artificial skin, the sensing elements are developed prior to the development of the basic mechanical structure of the artificial skin. Thus, the sensing functionality can be separated from the mechanical functionality, e.g. the restoration force to regenerate the off-state of the sensor after the release of an external indentation force does not have to be provided by the sensing elements themselves. This approach allows for the further reduction of the material volume of the sensing elements.

Manufacturing process According to the design paradigms proposed in section 3.2.7 no rigid elements can be introduced into sensor areas that will be subject to mechanical loading during the operation on a robotic system. Therefore, an all-polymer approach for the design of the electrodes is pursued. Consequently, the electrodes have to be manufactured applying a polymer material. Wakuda and Suganuma [173] propose a processing technology for the manufacturing of electrically conductive fibers based on silver particle filled silicone adhesive. The proposed material combination of a silicone based flexible matrix polymer with flake-shaped silver particles results in a high electrical conductivity of the non-strained fiber.

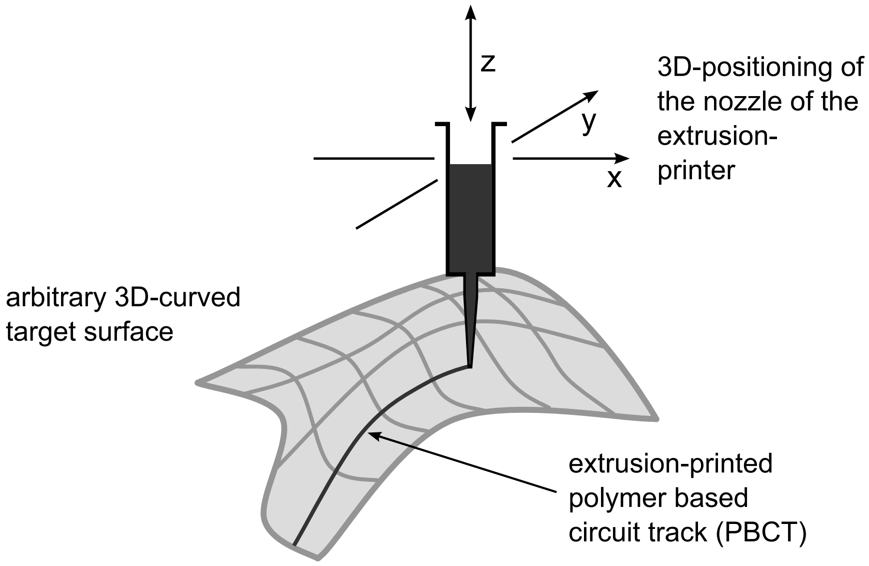


Figure 3.37: The application of the polymer based printed circuit onto an arbitrary 3D-curved target surface is enabled by the 3D positioning of the nozzle during the extrusion process.

A drawback of the application of flake-shaped filler particles is the low relative strain the fibers can be subjected to before breaking. While enabling a high electrical conductivity in the unloaded fiber, the shape of the particles results in a high strain dependency of the fibers. If the fibers are mechanically loaded, especially if stretched, the polymer matrix between the individual particles is elastically stretched. Thus, the particle-particle distance is increased and consequently the electrical resistivity of the entire fiber is increased. The authors propose a so called injection forming process that is based on the dispensing of a silver flake filled heat curing silicone rubber compound (conductive adhesive) into a heated oil bath. The conducted experiments for the evaluation of the strain dependency of the electrical resistivity show, that the high filler content and the aspect ratio of the filler particles allow only for a relative elongation of up to 15%. In addition, the proposed processing results in a limp polymer based conductive wire, that subsequently has to the handled and placed precisely in order to allow for the manufacturing of e.g. a tactile sensor with a high spatial resolution. While the handling and ultrasonic bonding of metal wires onto thermoplastic substrates is state of the art for the manufacturing of bendable circuit boards, the handling and precise placement of the elastic pre-extruded conductive polymer wires poses additional challenges for the precision of the processing machinery. As the electrical conductivity of the polymer wires depends on the strain of the wire, no mechanical stress may be introduced in the polymer wire during the handling and fixation of the limp polymer wire on the substrate.

To avoid this drawback, within this thesis an alternative approach based on the simultaneous extrusion and placement is proposed. This process is referred to as direct-extrusion printing, see figure 3.37. Therefore, the standard process of extruding particle filled polymer matrixes is adapted in order to create a flexible production process for the arrangement of the polymer based electrodes in the desired matrix configuration. Figure 3.38 outlines the principle of the direct-extrusion printing process. The electrically conductive polymer is extruded through a nozzle while the tip of the nozzle is positioned to the desired location of the PBCT on the target geometry. The major challenge for the manufacturing is the defined placement of the PBCT in z-direction. On one hand, it is desired to enable a defined off-state, thus the intersecting PBCT should not be in physical contact if the sensor is unloaded. On the other hand the initial sensitivity depends of the offset distance that has to be covered before the PBCT come into physical contact and a transition resistivity can be measured. Therefore, the manufacturing process has to enable a precise placement and fixation of the PBCT onto the target structure. Figure 3.38 depicts the flow phenomena within the nozzle. In order to allow for a constant

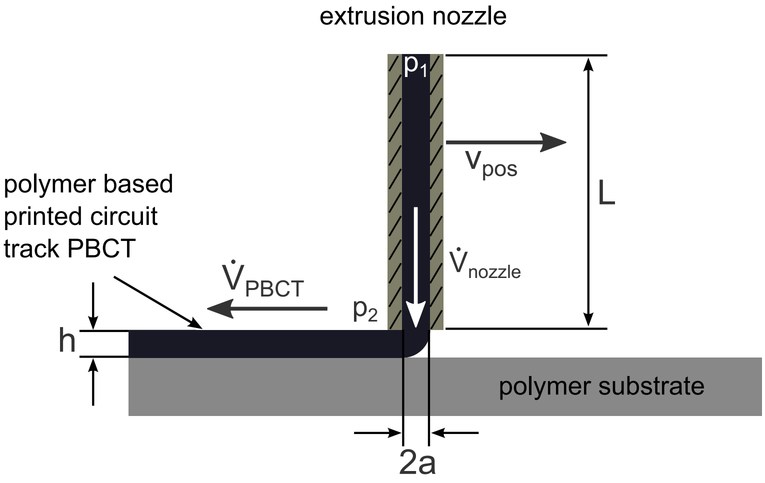


Figure 3.38: Extrusion printing process for PBCT with cylindrical cross section

height h of the PBCT the positioning velocity V_{pos} has to be adapted to the volume flow of the extruded PBCT. The derivation of the volume flow of Newtonian fluids in a cylindrical tube is presented in the appendix A.1, according to Kuhlmann [74] P.212 - P.214. The derived relation between the volume flow and the geometry of the tube and the difference in pressure can be summarized as:

$$\dot{V} = \frac{\pi a^4}{8\mu}\frac{\Delta p}{L} \tag{3.10}$$

This relation shows, that the inner diameter $(2 \cdot a)$ of the extrusion nozzle for the manufacturing of the PBCT restricts the flow rate $\dot{V}_{nozzle}$ and thus affects the speed of the nozzle positioning. In order to enable a reproducible cylindrical shape of the PBCT the nozzle has to be displaced by the defined positioning velocity v_{pos}. For PBCT with a cylindrical cross section the width b of the PBCT equals the height $b = h = 2 \cdot a$. Thus, the area of the cross section of the PBCT is

$$A_{PBCT} = h^2\pi \tag{3.11}$$

Hence the flow velocity of the PBCT is

$$\dot{V}_{PBCT} = h^2\pi \cdot v_{pos} \tag{3.12}$$

and

$$\dot{V}_{PBCT} = \dot{V}_{nozzle} \tag{3.13}$$

and the positioning velocity

$$v_{pos} = \frac{\dot{V}_{PBCT}}{h^2\pi} \tag{3.14}$$

the pressure gradient $\Delta p = p_1 - p_2$ can be estimated for the desired width of the PBCT, the geometry of the nozzle and the dynamic viscosity of the desired polymer material:

$$\Delta p = 4\mu \frac{w_{max}}{(\frac{b}{2})^2} L \tag{3.15}$$

For Newtonian fluids the mean velocity is $w_{max} = 2\bar{w}$. For the manufacturing of a PBCT with circular cross section the positioning velocity has to equal the mean velocity of the volume flow of the extruded polymer:

$$v_{pos} = \bar{w} \tag{3.16}$$

$$\Delta p = 4\mu \frac{2\bar{w}}{(\frac{b}{2})^2} L = 32\mu \frac{v_{pos}}{b^2} L \tag{3.17}$$

Thus, the pressure difference required for the extrusion printing process depends only on the viscosity of the polymer material and the geometry of the nozzle. The viscosity, e.g. for an uncured silicone depends on the flow state described in the flow law. The characterization facilities, available for this thesis, did not allow for the acquisition of the flow law of the applied non-Newtonian polymers compounds. Therefore, the flow characteristics of the applied polymer material have to be experimentally determined and adapted to the available processing machinery. The material properties enabling the proposed manufacturing process are outlined in section 3.4.2.

Design parameters Initial tests revealed a quasi binary sensor output to external mechanical loading of the PBCT with circular cross section. Therefore, a testbed for the investigation of the relation between applied normal force and the transfer resistivity is developed and implemented in Leupolz [89]. The setup is based on the experimental setup designed in Schnös [135]. Figure 3.40 depicts the applied test principle. In order to evaluate the course of the electrical transfer resistivity at the crossing point of two intersecting PBCT two test specimen are manufactured. The PBCT are directly applied on a gold contact surface in order to prevent the acquisition of changes of the transfer resistivity between the metal contacting and the PBCT. The testbed developed in Leupolz [89] consists of a precision linear axis with a stepper motor for the generation of the normal indentation force. The two intersecting PBCT are fixated between the linear axis and the surface of a precision scale. Both, the applied normal force and the resulting transfer resistivity are acquired. Figure 3.41 depicts the dependency of the electrical resistivity at the contact area of two intersecting PBCT. A circular cross section results in a quasi binary decrease of the resistivity as a result of the applied normal force. In contrast, a triangular cross section offers the desired analog output that allows for the acquisition of the applied normal force. In order to enable the desired transduction properties the shape of the cross section of the PBCT has to be adapted, e.g. from circular to triangular, see figure 3.39(a-b). There are countless patents and patent applications describing approaches towards adaptable transduction properties of tactile sensors based on the shape of the cross section of the applied polymer electrodes. One of the most sophisticated approaches is presented by Peterson et al. in [120]. In the patent application the authors disclose a tactile sensor with optimized relationship between changes in external applied pressure and resulting change in contact surface area. The authors refer to the polymer based electrodes

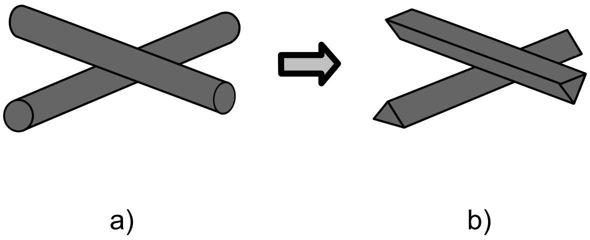


Figure 3.39: The adaptation of the relation between the applied external load and the resulting change in contact area between two intersecting PBCT is enabled by the replacement of the circular cross section with a triangular cross section.

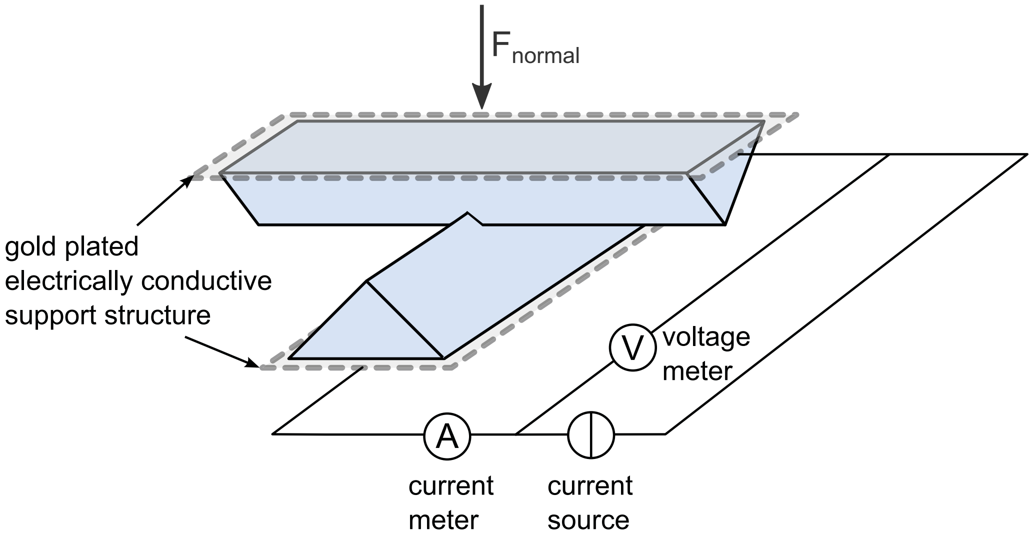


Figure 3.40: Initial test of the evaluation of the transduction properties of two intersection PBCT with triangular cross section; Figure adapted from Schnoes [135].

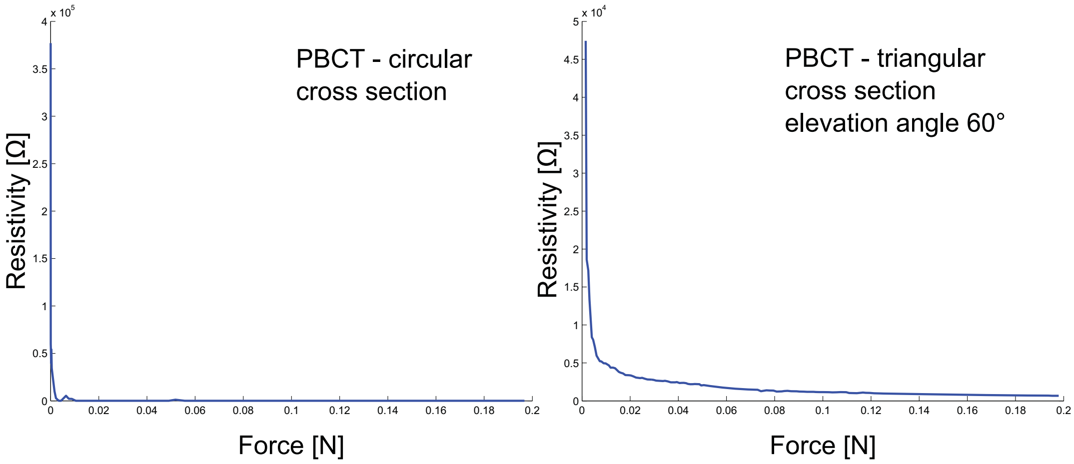


Figure 3.41: The adaptation of the relation between the applied external load and the resulting change in contact area between two intersecting PBCT is enabled by the replacement of the circular cross section with a triangular cross section. Figure adapted from Leupolz [89]

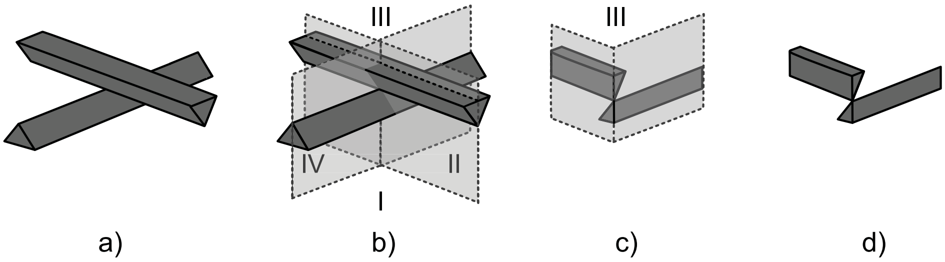


Figure 3.42: To reduce the computational effort for the simulation of the transduction properties of a taxel (a), the symmetry of the setup (b) is utilized to reduce the model to a quarter of the taxel (c,d).

as conductive rods and state, that:

> "The conductive rods are formed with a selected cross-section, in order that changes in the amount of pressure exerted on the sensor will produce corresponding changes in the contact surface area, and hence a change in the electrical contact resistance [...]."

The proposed shape of the cross section of the electrodes resembles the cross section of a boat hull. The presented "conductive rods" provide the sensor's restoration forces while at the same time enable the transduction. According to the functional partitioning proposed in section 3.2.7 the cross section of the PBCT proposed within this thesis is designed independent of the required restoration forces. Therefore, a simplified triangular shape of the cross section of the PBCT is proposed. Figure 3.39 depicts the replacement of cylindrical with a triangular cross section. A model for the relation of the z-deviation and the contact area is proposed by Schnös [135]. The results of the study with respect to the relation between normal displacement and contact surface area are summarized in figure A.1 in the appendix. The extend of the contact surface area depends on the normal deviation of the upper PBCT, the

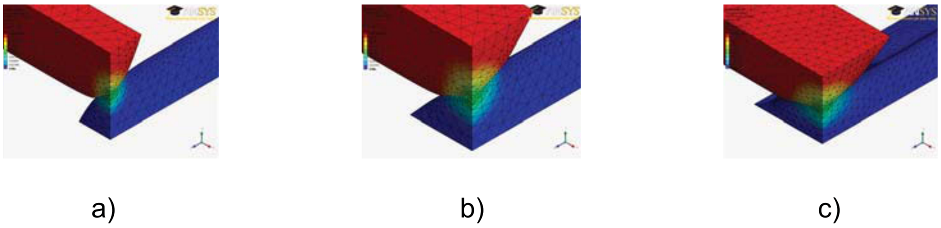


Figure 3.43: The angle of the PBCT is varied in order to evaluate the adaptability of the transduction properties based on an alternation of the angle of the triangular PBCT. The simulation is conducted for an angle of 30° (a), 45°(b) and 60°; figure adapted from Krauß [73].

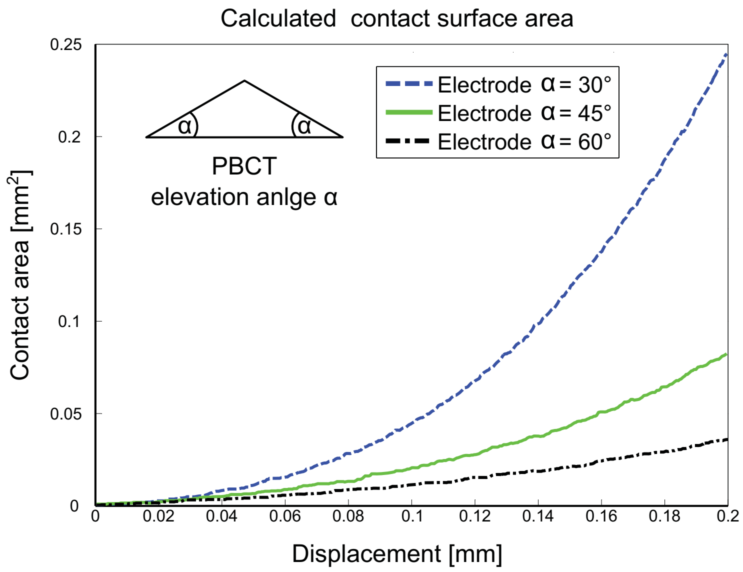


Figure 3.44: The above figure depicts the results of a FEM analysis conducted in Krauß [73]. An external indentation force results in a deflection of the upper PBCT and thus results in a change of the contact surface between the triangular PBCT. Depending on the elevation angle of the PBCT the dependency of the contact surface area from the displacement in normal direction can be adapted. Thus, the transduction properties of the normal force acquisition taxel can be scaled to the requirements of the application site on a robotic system; figure curtesy of Krauß [73].

relation is depicted in figure A.1 in the appendix. In order to investigate the correlation between the displacement in normal direction and the resulting change in contact surface area for different angles of the PBCT a FEM simulation is conducted in Krauß [73]. In order to reduce the computational effort the symmetry properties of a taxel based on two intersecting PBCT is utilized by simulating only a quarter of the taxel, see figure 3.42. Figure 3.43 depicts the applied PBCT angles applied for the simulation. The FEM simulation conducted in the study of Krauß [73] exemplifies the dependency of the relation of the between the normal displacement and the resulting change in contact surface area. The results of the FEM simulation promote the application of a triangular cross section of the PBCT. The alternation of the angle of the triangular PBCT enables the adaptation of the relation between the displacement and the resulting change in contact surface area. Figure 3.44 depicts the relation between normal displacement and resulting change in contact surface area between two intersecting PBCT. The relation is simulated for an PBCT angle of $30°$, $45°$ and $60°$.

Shear force acquisition

For the application in robotic grippers and hands the acquisition of the shear component parallel to the surface of the robotic gripper is important for the evaluation of grasp stability. The distributed acquisition of shear forces in artificial skin allows for the generation of the information if the contact forces between the skin surface and the gripped object are sufficient to transmit the desired manipulation forces. Thus, a stable grasp can be maintained during dexterous manipulation by adjusting grip forces to changes of the orientation of the gripped object. Based on the acquisition of shear forces a robotic grasp force adjustment comparable to the functionality observed in humans might be feasible. The acquisition of shear forces can be based on two principle approaches: Indirectly, based on the acquisition of the output of multiple normal force acquisition taxels or directly, via specialized shear force acquisition taxels.

Indirect shear force acquisition The indirect acquisition of the shear force is based on the evaluation of the output of multiple normal force acquisition taxels in combination with a surface structure on top of the group of taxels. The surface structure transforms the external shear force to normal forces acting on the individual taxels. The evaluation of the shear force is based on the data stemming from multiple normal force taxels. Often a computational model is applied for the calculation of the actual exerted shear force. Lee et al. [82] present a sensor setup that allows for the acquisition of normal and shear forces based on the measurement of changes in capacitance in a set of four adjoining capacitors. The direction of the indentation force is calculated from the excitation of the individual capacitors. According to the authors the macrostructure of the surface, here square bumps, are manufactured by an etching process of a silicon mould that is subsequently spin coated with silicone. The authors state, that the accuracy of the calculation of the direction of the indentation force depends on the material properties of the indenting object. For rigid objects that indent the surface bumps from one side an error occurred. While the authors state, that the scenario of a rigid indentation object is rather unlikely, a dependency of the reliability of the sensor data from the material of the indenting object is not acceptable in safe pHRI.
Ando et al. [3] present a tactile sensor based on ultrasound, that enables the acquisition of the indentation force in six axis. The presented formulas illustrate the complexity of the backward calculation of the indentation force vector. Furthermore the presented design is very well suited for the application in e.g. a robotic fingertip as the sensor provides information regarding the resulting indentation force vector. No spatially distributed information regarding the local shear force on the surface

can be derived from the presented sensor design. Nevertheless, the spatially distributed acquisition of pure shear forces might be feasible in an array setup. The mechanical structure of the sensor therefore would have to insulate the individual sensing cells from each other with respect to to propagation of the ultrasonic waves. While the lateral insulation could be implemented by the introduction of air filled gaps between the sensory cells, the technical feasibility of the insulation in areas where the sensory cells are connected mechanically, e.g. by a covering polymer layer, might prove difficult as the structure-borne sound would result in a crosstalk between the individual sensory cells.

Vásárhelyi et al. [168] investigate the effects of elastic cover layers with respect to the posed inverse calculation problem of the properties of the contact based on the data from a tactile sensor covered with a structured polymer surface. The authors state, that the hemispherical structures on the surface of the tactile sensor enable an independent coding of the normal- and shear-components of the external load. Applying the proposed elastic normal force transduction setup a sensor approach towards indirect shear force acquisition can be derived if the sensor surface is structured. This surface structure propagates the combined normal and shear force components of the indentation force vector to the sensory elements distributed below the surface structure. The tangential components of the forces are converted to normal forces exerted to the single tactile elements. The comparison of the normal forces acting upon the individual sensory elements allows for the calculation of the original spatial direction of the indentation force vector. Thus, a computational model of the surface structure and the underlying sensory elements is required to calculate the fraction of the shear forces. The introduction of a surface structure that covers multiple sensory elements results in a decreasing spatial resolution of the sensor. In addition the transduction properties of the sensor become location dependent as discrete direction sensitive structures are formed.

The required material processing for the sensory elements is identical to the processing required for the normal force acquisition sensory elements. In addition to the sensory elements a structuring of the sensor surface is required. The design parameters for the surface structures are diameter and height of the surface structure. Depending on the ratio between diameter and height of the surface structure the sensitivity for normal and shear forces can be tuned.

The manufacturing of tactile sensors for the acquisition of shear forces based on surface structuring requires the integration of a higher number of tactile elements as each shear sensitive taxel consists of multiple normal force taxels. Therefore, in general the spatial resolution of tactile sensors that are able to measure shear forces via surface structuring is smaller compared to normal force sensing tactile

sensors.
In order to enhance reliability of the information derived from the sensor and reduce the computational effort for the calculation of the direction of the force vector an approach towards direct shear force acquisition is derived in the following subsection.

Direct shear force transduction In contrast to Vásárhelyi, Noda et al. [106] state, that the backward calculation of the indentation vector "becomes a serious problem" if large surface areas of a robotic system have to be covered with tactile sensors. Therefore, the authors propose a sensor setup that is based on sensitive structures that are embedded into a polymer based surface layer. The orientation of the sensitive elements allows for the measurement of the deformation of the polymer layer resulting from tangential loads. The presented approach aims for the conditioning of the tangential load into a measurable domain. The lateral displacementis transformed into a bending of the sensing elements. While the sensor shows a sensitivity in the order of single-digit kPa), the sensory elements are based on MEMS structures etched from a silicon wafer. Thus, the sensory elements themselves are fragile and have to be embedded in a polymer material. Hence the hard-soft interface is located within the mechanically loaded area and might fail in case of an overload.
The concept of the direct acquisition of the shear component of an arbitrary indentation load might be promising for the development of shear sensing elements.
An approach for the acquisition of the change of the surface area is proposed by Rocha et al. [126]. The authors present a tactile sensor that is capable to acquire the indentation force in three dimensions. The design is based on a set of capacitor plates where four electrodes are arranged in a two by two array on the bottom of a polymer separation layer and a reference electrode is placed in the center of the array on top of the polymer layer. Tangential and combined forces result in a lateral displacement of the top reference electrode with respect to the center of the two by two array. The applied solid polymer layer between the electrodes presumably results in a comparatively low sensitivity of the sensor setup. The resulting change in the individual capacitors allows for the calculation of the 3D displacement of the sensor. The authors omit the complex task of the calculation of the vector of the indentation force. Nevertheless, the principle of the change of the surface area may be promising for the design of selective shear force sensing elements. The mechanical structure of the tactile surface sensor therefore would have to condition the external stimulus in order to load the shear sensitive structures with pure shear force.

Noda et al. [106] present an approach towards direct shear force detection based on silicon cantilevers that are equipped with a piezo-resistive layer. The cantilevers are vertically arranged and encapsulated in a soft silicone layer. An external shear load results in a bending of the cantilevers that results in a measurable change in electrical resistivity. According to the design paradigms proposed in this thesis no rigid structures may be introduced into the mechanically loaded sensing area. Therefore, an approach towards direct shear force acquisition based on polymer structures is desirable.

Park et al. [117] present a direct shear force acquisition sensor based on channels filled with a conductive liquid. An external load results in the displacement of the conductive liquid. The decrease in volume results in a change in electrical conductivity that can be acquired at the ends of the polymer encapsulated fluid channels. According to the authors the presented sensor prototype is capable to directly measure strains up to 100%. The major drawback of the proposed sensor setup is the lack of scalability as multiple independent fluid channels are required to form a taxel for the acquisition of the direction of an external shear force.

Concept In Strohmayr [158] the analysis of the undesired effects during the compression of particle filled polymer blends led to the idea to turn the undesired parasitic effects, i.e. the increase of the electrical volume resistivity in particle filled polymer compounds subject to mechanical strain, into a transduction principle and utilize the effect for the direct acquisition of shear forces. The proposed setup subsequently has been patented in Smagt et al. [150]. An approach quite similar to this "new" transduction principle happens to be presented already in 1987 by Russell [128]. Russel proposed the application of "conductive rubber strain gages" that are fixated at the inner surface of a silicone based shell of a compliant fingertip setup. Russel states:

> "The availability of a new formulation of stretch sensitive elastomer provided the starting point for a sensor design which, it is hoped, will provide significant improvements over the original force sensor. The new sensor detects deformation of a flexible "skin" supported by a pad of polyurethane foam. This is in contrast to most other contact sensors, which usually respond to forces normal to their surface."

Thus, the presented approach is readily "tailored" to support the approach towards specialized strain sensitive taxels for an artificial skin for robotic systems pursued within this thesis. From the study of Russell [128] it can be concluded, that the direct acquisition of the shear component of the indentation force can be based on the measurement of the strain in the surface layer that results from the indentation force. According to the proposed functional partitioning the transduction properties of the sensory elements have to be optimized for the isolated acquisition of a modality of the external stimulus. Therefore, the design of the strains sensitive taxels has to reduce the sensitivity of this structure to normal indentation forces. Figure 3.46 depicts the estimated deformation resulting from an external shear force. The goal of the design of shear force sensitive taxels is the generation of a sensor setup that exhibits a high sensitivity towards the shear component of the indentation force vector while reducing the sensitivity towards normal indentation forces. Therefore, the application of a surface structure for local strain enhancement is proposed, see figure 3.45. An external shear force is thus conditioned by the surface structure in order to enable the acquisition of local differences in surface strain. The shape of the proposed surface bump affects the transduction properties. Lee et al. [82] report measurement errors resulting from a shear force exerted to the applied truncated pyramid-shaped surface bumps.

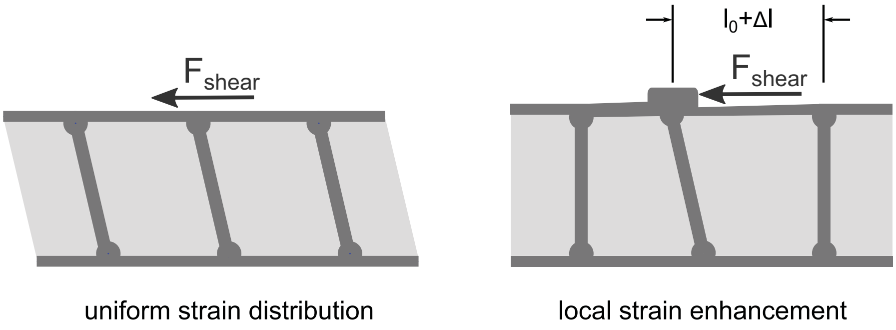


Figure 3.45: Depending on the form of the applied surface structuring the external shear force is propagated to the strain sensitive structures in the sensitive layer.

In order to enable transduction properties that are independent of the direction of the exerted shear force hemispherical surface bumps are proposed, see figure 3.46. Figure 3.46 depicts the conditioning functionality of the proposed hemispherical surface structure. An external shear force acts upon the side of the surface structure and thus causes a deviation of the surface structure. As a result, the surface of the taxel is strained for its initial length l_0 to a length $l_0 + \Delta l$ depending of the external shear force. Thus, the external shear force is conditioned to a locally enhances strain of the sensor surface. According to the design paradigm of an all-polymer sensor setup, as presented in section 3.2.7, the sensory cells for the acquisition of shear loads have to be based on a stretchable polymer material. In their patent from 1985 Dario et al. [22] propose a multifunctional tactile sensor based on "piezo- and pyro-electric (ferroelectric) properties of polymeric materials". With respect to

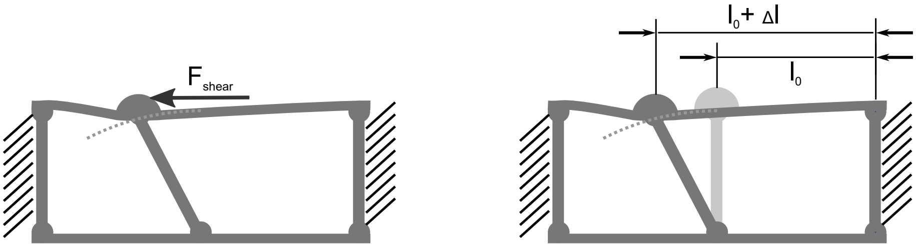


Figure 3.46: Deviation of the strain sensitive structures as a result of the geometry of the surface structure.

the acquisition of strain the authors state, that

> "[...] the protective plastic [...] can be thermo-formed in order to obtain ridges, which act as levers to amplify superficial strain and to induce larger strain in the sensors."

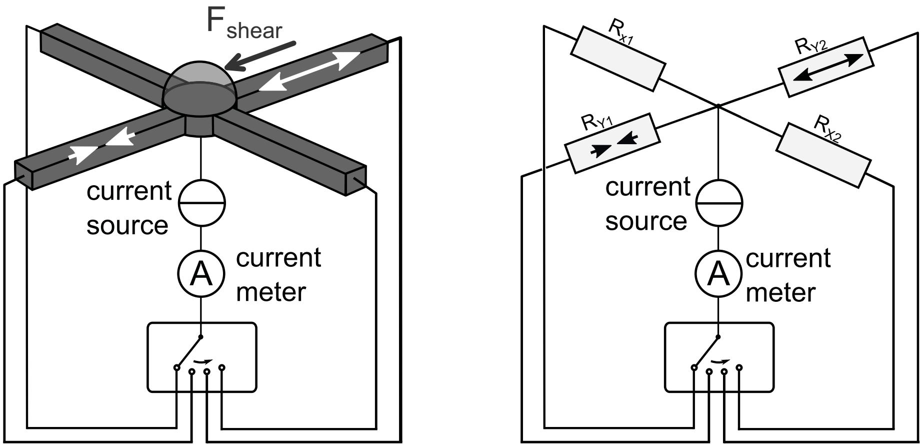
According to the authors:

> "The major limitation of ferroelectric transducers in general is the lack of truly static response [...]."

Therefore, for this thesis an alternative transduction effect is proposed for the acquisition of external shear forces. Inspired by the approach of Russell [128] polymer based strain sensitive structures (PBSS) are proposed for the acquisition of local strain in the sensor surface. The sensor prototype described by Russell [128] consists of a line of eight strain sensitive taxels. Thus, the setup is restricted to the acquisition of strain in only one direction. Therefore, the proposed approach is adapted for the direct acquisition of shear forces. In order to allow for the acquisition of arbitrary strain direction, four PBSS are combined to form a strain sensitive taxel that is able to acquire the direction of the external shear force, see figure 3.47(a). Figure 3.47(b) depicts the equivalent circuit diagram for a strain sensitive taxel. The combination of elasticity and strain sensitivity of resistive polymers allows for the design of overload proof strain sensitive taxels for the direct acquisition of the tangential component of an external indentation force.

Manufacturing processes With respect to the manufacturing process, Russell [128] states:

> "At present, the conductive material is cut to shape and then glued to the skin surface. However, the conductive polymer can be screen printed and therefore in the future it may be possible to manufacture the whole sensor by a sequence of printing operations."



a) b)

Figure 3.47: Design of a direct shear force acquisition taxel based on four polymer based strain sensitive structures (PBSS).

The direct extrusion printing process proposed for the manufacturing of the PBCT for the normal force acquisition taxels can equally be applied for the manufacturing of the PBSS. Similarly, the proposed direct extrusion printing process can be applied to implement the required surface structures. In contrast to the material properties required for the manufacturing of the PBCT, the material applied for the surface structure has to exhibit a comparatively low viscosity in order to allow for the dispensing of hemispherical surface structures.

Material properties Following the required material properties for the strain sensing elements are outlined. The so called percolation theory, e.g. described in [127] is an attempt to describe the effects that are considered to be responsible for the electrical conductivity within the polymer matrix. The dependency of filler fraction and resulting electrical conductivity is exemplarily depicted in figure 3.48. Depending on the content of filler particles the measurable electrical volume conductivity of the polymer compound varies. The relation depicted in figure 3.48 can be subdivided into three sections. In section I, the low concentration of the electrically conductive filler particles results in an electrical insulation of the individual particles by the non-conductive matrix polymer. Therefore, the electrical conductivity is low. Within section II an increase of filler particle content results in the formation of conductive pathways through the non-conductive polymer matrix. This section of-

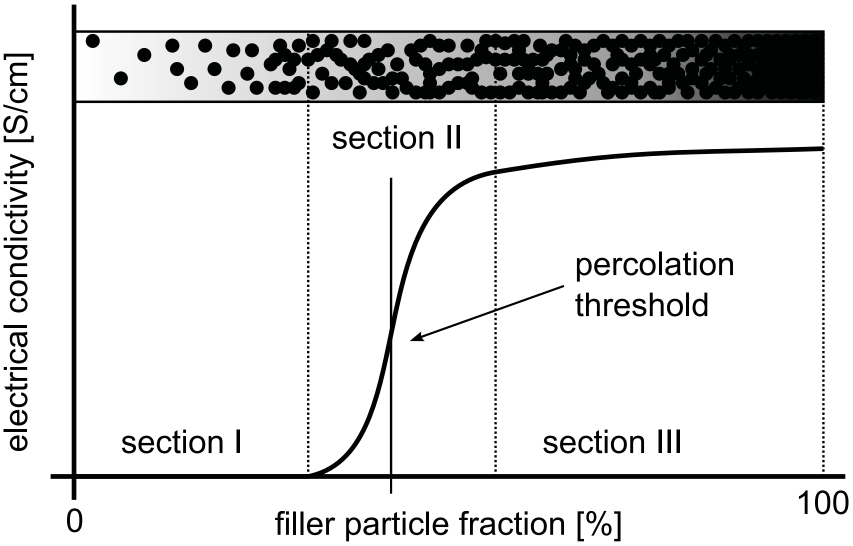


Figure 3.48: The percolation phenomenon, describes the non-linear relationship between electrical conductivity and filler particle content in particle-polymer matrix compounds; Figure adapted according to Domininghaus [26].

ten is referred to as the percolation threshold. Within this section small changes in filler concentration result in large changes in electrical conductivity. In section III the electrical conductivity of the polymer compound becomes almost independent of the filler particle content as numerous electrical pathways are formed within the polymer matrix. Besides the alternation of the electrical conductivity, the introduction of filler particles always affects the mechanical properties of the resulting polymer-filler-compound. The interested reader may be referred e.g. to Princy et al. [124].

The effects of mechanical loading to the electrical conductivity of polymer-filler compounds has been intensely studied. The effect of axial stretching to the electrical resistivity in carbon black filler silicone is analyzed e.g. by Kost et al. [72]. The authors derive a model for the "strain dependent electrical resistance of carbon black loaded silicone rubber". The model is presented as adapted from the model describing the mechanics of biological material presented by Fung in e.g. [36]. A more recent study analyzing the electrical conductivity of silicone rubber filled with carbon black and carbon fibers is presented by Sau et al. [130]. The results with respect to the strain dependency of the electrical conductivity reveal a non-monotonic relationship. While for relative elongations up to approximately 25% a sharp increase in electrical resistivity is observed, effects within the polymer-filler composite result in a subsequent decrease of the electrical volume resistivity for relative strains exceeding approximately 35%. Thus, a careful design of the strain sensitive taxels is required in order to enable the monotony required for the acquisition of relative strain.

Most of the commercially available electrically conductive polymers contain a filler content that is well above the percolation threshold in order to minimize the influence of mechanical deformation on the electrical properties of the material. Thus, specialized materials have to be developed in order to enable the required strain dependent mechano-resistive behavior. The transduction properties of PBSS can be adapted to the requirements of the application site on the robotic system by the alternation of the strain dependency of the electrical conductivity of the applied polymer-filler compound.

Slip detection

The detection of slippage can be based on the acquisition of vibrations in the the artificial skin resulting from the stick-slip effect, caused by a relative motion between an object and the artificial skin surface. According to Scheibert et al. [132] in humans the "tactile perception of fine textures (spatial scale < 200 micrometers) is mediated by skin vibrations generated as the finger scans the surface." An early technical approach towards the acquisition of vibrations in robotic fingertip is presented by Tremblay and Cutkosky [165] in 1993. The authors propose the acquisition of slip based on accelerometers located within a compliant robotic fingertip. With respect to the integration of the proposed sensor setup into a robotic system the authors conclude, that:

> "Obviously, one could not hope to use an accelerometer based sensor during rapid motion of the manipulator due to the presence of large mechanical vibrations that would render the incipient slips undetectable".

In addition, the proposed all-polymer design paradigm prevents the introduction of rigid elements into the mechanically loaded sensing area.

An early work regarding dynamic tactile sensing is presented by Howe and Cutkosky [55]. The authors present an approach towards tactile sensors that are dedicated to the acquisition of mechanical transients. The applied piezo-electric polymers acquire changes in mechanical stress below a rubber based skin of a robotic finger and allows for the detection of surface structures with a hight of $6.5\mu m$.

The more recent work of Yamada et al. [186] is based on a design approach for robotic fingertips with elevated superficial ridges. In order to acquire incipient slip PVDF film strips are introduced into the the superficial rubber based ridges. The major disadvantage of the presented approach is the hard-soft interface between the PVDF strips and the metal based readout wires. According to the authors the presented prototype is based on two PVDF strips that are

> "[...] longer than the width of the skin because the glued connection parts between the PVDF strip electrodes and signal wires are harder than the silicone rubber material. If the harder part was in the artificial finger skin, mechanical behavior in the artificial finger skin would be changed."

Thus, the presented setup prevents the successful introduction of the sensitive structures into a real robotic fingertip.

Teshigawara et al. [163] present a slip sensor based on the acquisition of changes in the electrical resistivity of a silicone rubber filled with carbon particles. While the authors conclude, that the sensor output results from changes in electrical volume conductivity within the polymer material, the presented approach based on a top and bottom metal electrode is likely to result from the alternation of the transfer resistivity between the metal electrodes and the polymer material. Again, the all-polymer design paradigm prevents the application of the presented approach.

Concept The basic idea for the acquisition of vibration is based on the spatial separation of the vibration sensing element from the mechanically loaded sensing area. This approach allows for the application of dedicated transduction hardware without compromising the all-polymer design paradigm. In order to allow for the spatial separation of the transduction hardware from the sensing area a medium is required that can be applied in an all-polymer artificial skin. Loeb et al. present in their patent [92] a robotic fingertip with a specialized pressure sensor for the acquisition of changes in pressure in a polymer enclosed cavity. If the volume of the tactile elements is capsulated against the environment a global change of pressure can be acquired resulting from the indentation force that is exerted on the sensor surface. The integration of the robotic fingertip presented by Loeb et al. [92] into robotic systems for real world application might be somewhat hindered by the cumbersome filling process and complicated sealing off of the fluid filled cavity. Therefore, the concept of the global pressure acquisition approach presented by Loeb et al. [92] is adapted for this thesis. In order to facilitate the introduction into a robotic system the propagation of the vibration to the specialized sensing element via a fluid is replaced by the propagation via an enclosed volume of air or gas. Accordingly, the dynamic pressure sensor applied as transduction element by Loeb et al. [92] is replaced by a microphone.

The concept for the detection of slip is presented according to the solution derived in Schneider [134]. Figure 3.49 depicts the principle setup for the acquisition of vibrations in an all-polymer artificial skin setup. In order to allow for the remote acquisition of the vibration the sensing area of the artificial skin is encapsulated. Thus, a vibration induced from the relative sliding between an object and the surface of the artificial skin results in changes in pressure in the enclosed cavity. To enhance the induced vibrations a structuring of the sensor surface is proposed by Trembay and Cutcosky [165]:

> "The skin is covered with "nibs", or projections, that form local contact regions that can slip independently from one another and produce small vibrations."

Irrespective of the location of the vibration the global pressure within the cavity is altered by the induced vibration. A drawback of this approach is the loss of the spatial resolution of the location of the induced vibration. This loss of information

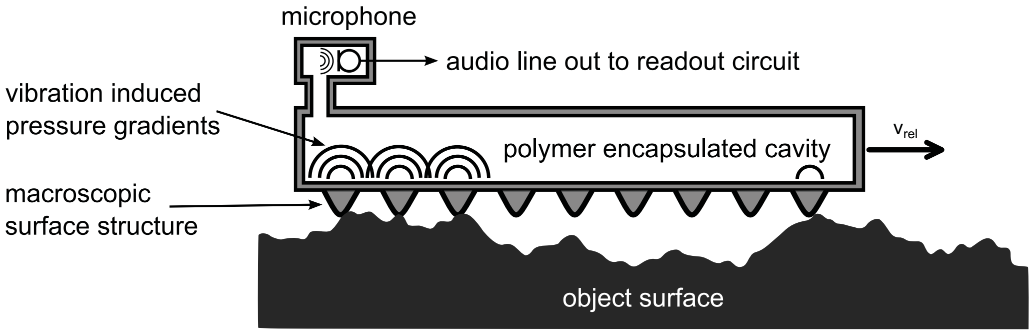


Figure 3.49: A polymer encapsulated cavity within the artificial skin enables the propagation of pressure gradients to a miniature microphone outside the mechanically loaded sensing area. The surface structure of the artificial skin promotes stick-slip phenomena during relative sliding motion between the artificial skin surface and the object; figure adapted from Schneider [134].

can be compensated if the information regarding the location of the contact is derived from the normal force taxels. The remote location of the mechanically rigid transduction elements results in the preservation of the required collision tolerance of the artificial skin. In addition, the replacement of the fluid with a gas enables the manufacturing of the polymer enclosed cavity based on the processes proposed for the manufacturing of the PBCT and the PBSS.

3.3.2 Mechanical structure

Resulting from the functional partitioning proposed in section 3.2.7, the mechanical structure of the artificial skin needs to provide a broad range of functionality. From a sensor design point of view the central functionality of the mechanical support structure is to spatially fixate the sensing elements in the desired configuration. In addition, the mechanical structure has to provide the restoration force required for the recovery of a defined off-state of the sensitive elements after the release of an external load. A second functionality required for the solution of the goal conflict between high initial sensitivity and a collision tolerant design is the mechanical conditioning of the external stimulus to the location and transduction properties of the sensing elements. Further, the mechanical structure needs to enable the desired scalable spatial resolution and the adaptable transduction properties. With respect to the operation on a robotic system, the mechanical structure is required for the transmission of desired and undesired interaction forces in case of intended robotic manipulation or unintended collision respectively. In order to support the desired increase of a safe physical interaction, the mechanical structure of an artificial skin is required to provide mechanical damping properties that allow for the dissipation of the kinetic energy introduced in case of a collision. Following a concept for a multi functional mechanical structure of an artificial skin is derived.

Concept

From the domain specific design of the sensing elements a set of requirements arises. The most prominent, the required deformability which is prerequisite for an enhanced dexterity and safety, is accounted for by the design of the mechanical structure according to the proposed design paradigms introduced in chapter 3.2.7. Therefore, an all-polymer design of the mechanical structure is pursued. The primary functionality of the mechanical structure is the spatial fixation of the sensing elements in the desired configuration. The mechanical structure enables the fixation of the crossing points of the PBCTs and thus maintains the position of the taxels within the sensitive layer of the artificial skin. The mechanical structure support the lower set of PBCT while at the same time fixate the upper set of PBCT at a defined distance over the first set. In addition a macroscopic surface structuring is proposed enabling the mechanical conditioning of the external stimulus.

Reduction of the required input energy by spacer-separated foil Siegel et al. [147] argue, that the application of solid polymer sheets as the dielectric separation

layer of a polymer based capacitor affect the sensitivity of the sensor as the ideally incompressible rubber can not shun from the load. Therefore, the authors propose the introduction of voids into the polymer dielectric material in order to provide a volume where the polymer material can "escape" if the sensor setup is mechanically loaded. Figure 3.20 in section 3.2.7 depicts the concept of the designed density. The underlying idea is the introduction of geometrically defined voids into the mechanical structure of the artificial skin.
Therefore, the setup depicted in figure 3.50 is proposed for the mechanical structure of the artificial skin. The setup consists of two polymer based substrates, figure 3.50(a) that are mechanically connected via polymer based spacers, figure 3.50(b). The resulting spacer separated sandwich foil, figure 3.50(c) accounts for the proposed design paradigms and supports the solution of the goal conflict between high initial sensitivity and the required overload proof design. The proposed setup forms the basis for the implementation of an artificial skin according to the proposed design paradigms. With respect to sensitivity the spacers play an important role. Their shape, i.e. their length and diameter, greatly affect the mechanical transfer function of the taxels. Polymer based spacers are applied in order to maintain the distance of the different layers of the multi layer foil even if it is wrapped around edges with small curvature e.g. the rims of the robot's covering structure. The spacers convey the external mechanical load from the upper flexible substrate to the lower flexible substrate and thus to the robot's covering structure, see figure 3.51. External mechanical loading can result in normal as well as shear forces, therefore the spacers are mechanically fixed to the layers of the multi layer foil and are applied to propagate tangential forces to the underlying covering structure of the robot. The proposed spacer separated sandwich foil enables a lateral func-

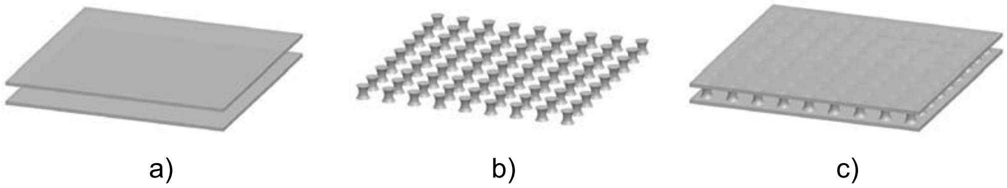


Figure 3.50: The reduction of the deformed volume by reduction of the designed density is implemented by the replacement of a solid polymer volume by a polymer based sandwich foil. The setup is based on two basic polymer foils that are separated by polymer spacers. The geometry and the fraction of the material volume of the spacers to the entire volume between the two polymer foils defines the designed density of the resulting spacer separated sandwich foil.

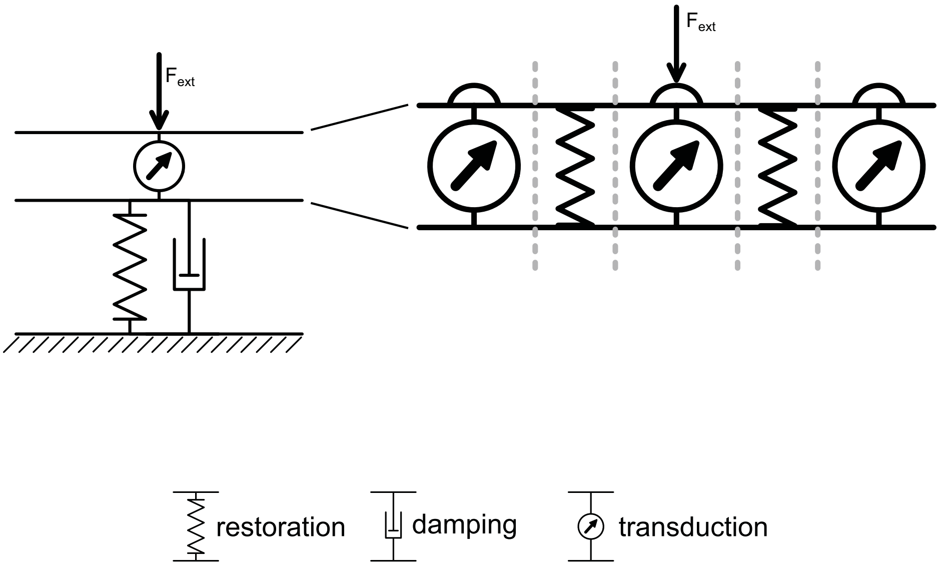


Figure 3.51: In order to solve the goal conflict between required robustness and high initial sensitivity a concept based on the lateral functional partitioning of the sensing layer is proposed

tional partitioning of the mechanical structure and enables the parallelization of the acquisition and transmission of interaction forces.

Lateral mechanical insulation The mechanical structure of an artificial skin can support the desired sensory capabilities by its design. Especially, the mechanical separation of the individual taxels is important for the desired high spatial resolution. Already Lederman and Pawluk [81] point out that the

> "[...] adjacent sensing elements within a tactile sensor may be passively triggered by the mechanical response of the sensor covering to deformation".

Therefore, a mechanical decoupling of the adjacent taxels is required. Thus, the mechanical fixation of the taxels in space has to be performed by a structure that minimizes the lateral distribution of the mechanical stimulus. Siegel et al. [147] argue, that what the authors call "response overlap between adjacent cells" is desirable in order "avoids the dead zones between (adjacent) cells". One may thus conclude, that the mechanical structure has to provide lateral mechanical separation of the individual taxels, jet has to ensure, that no "dead zones" are formed by the separating mechanic support structure. The receptive fields of the sensory cells of the human fingertip are overlapping, see 3.2.1. The effects of lateral distribu-

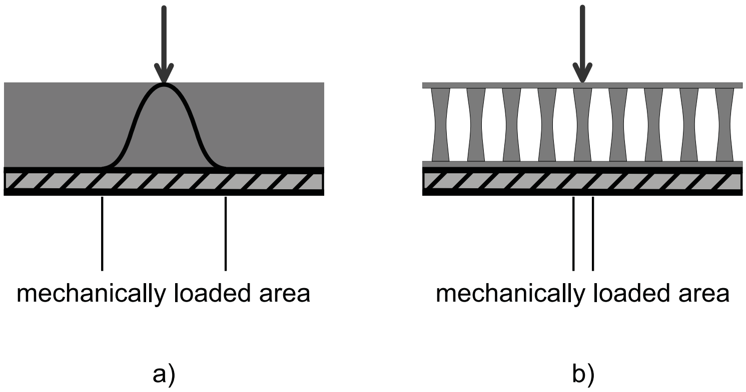


Figure 3.52: The application of a solid polymer material results in the lateral distribution of a point contact at the sensor surface. The introduction of geometrically defined voids, that enable a direct mechanical coupling in vertical direction and at the same time inhibit the lateral propagation of the point contact facilitates the calculation of the location of the point contact on the surface of the sensor.

tion of a point load on the surface would have to be accounted for in the readout electronics and software. Figure 3.52(a) depicts the effect of the lateral distribution of a point load at the surface of a solid polymer material. In order to reduce the computational effort a spacer separated sandwich foil is applied that supports the mechanical lateral insulation of neighboring taxels, see figure 3.52(b).

Conditioning of the external stimuli towards the location of the specialized taxels The sensitivity of the resulting artificial skin is based on the interaction between the sensing elements and the mechanical structure. A technical adaption of the stimulus conditioning mechanism in human skin is being investigated by Gerling et al. [38]. The major finding is the contradiction of the widespread theory that in human skin the papillary ridges are mechanically coupled with the ridges of the dermo-epidermal junction. The authors state, that the simulation of the interplay of the different skin layers suggests that the papillary ridges contribute to the mechanical conditioning of the stimulus towards the sensory cells. The principle of conditioning an external stimulus to the sensory elements is applied by Martin et al. [95]. The authors present an approach that is based on commercial tactile sensors pads that are integrated into the gloves of the NASA robonaut. Beads are sewn into the textile material of the gloves of the NASA robonaut hands and act as "force concentrators" over the force sensors. While the basic concept of the concentration of the indentation force towards the sensory elements appears to be promising the technical feasibility of rubber based force concentrators including the complex assembly process resulted in the abandoning of the concept.

Payeur et al. [118] introduce so called "protruding round tabs" into an elastic covering of a commercial FSR sensing array. (Please note, that already in Siegel et al. [147] the application of a "sheet with protruding round tabs" is proposed in order to overcome the incompressibility of silicone rubber). In addition, Payeur et al. propose to introduce geometrically defined voids into the elastic cover in order to allow for the tabs to expand laterally without affecting adjacent taxels. According to the authors, the application of these tabs counters the lateral mechanical blurring effect observed in solid polymer covers for tactile sensing arrays.

An internal mechanical structure for the concentration of the external load towards the sensitive areas is presented by Yamada and Cutkosky [185]. The authors propose the application of a surface structure referred to as "tactile head with tetrahedral core" and internal so called "pressure transmitting nibs". This setup allows for force acquisition in three degrees of freedom.

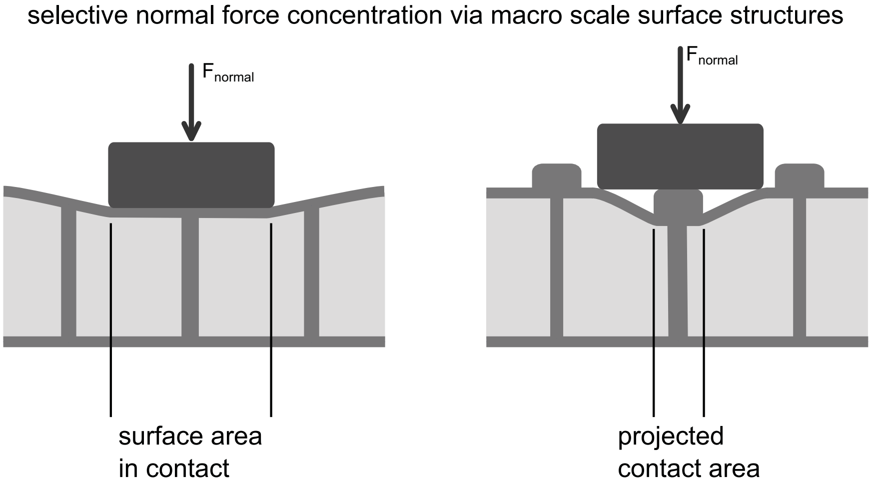


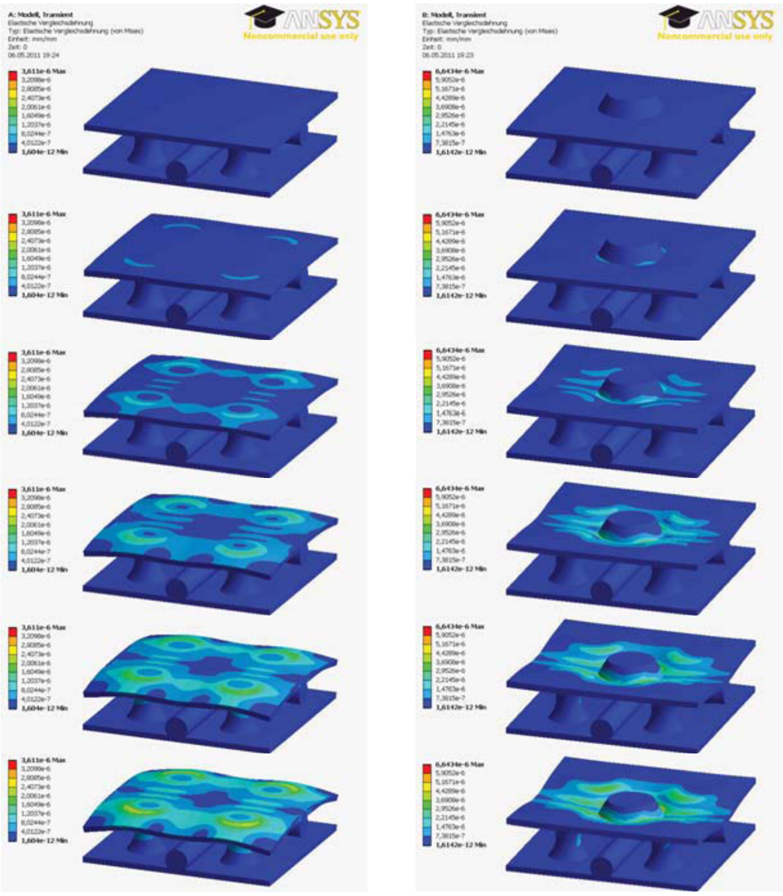
Figure 3.53: Concentration of the indentation force to the sensitive areas; by the introduction of surface structures the contact area is minimized. Thus, the pressure that is exerted by the indenting object is virtually increased.

A tactile sensor for the acquisition of normal and shear forces based on changes in electrical capacitance of a set of capacitors is presented by Lee et al. [82]. The authors propose the structuring of the surface of the tactile sensor to enable the transduction of shear forces. The applied truncated cone surface structure mechanically conditions the applied shear load to a subset of four capacitors that are sensitive to normal force. The authors report, that the sensor provides an erroneous output if the load is applied to the side of the surface structure. The reported error presumably is caused by the anisotropic mechanical conditioning. Therefore, the transduction properties of an individual taxel are likely to depend on the angle between the surface normal and the vector of the applied load. This characteristics render the sensor useless for real-world application in a robotic system. An alternative approach based on the acquisition of changes in the electrical resistivity is presented by Su et al. [160]. The authors apply mechano-resistive polymer structures based on carbon nano tubes (CNT) that are dispersed in silicone. In a molding process the mechano-resistive polymer structures are arranged on a millimeter scale bump shaped silicone structure. The shape of the macroscopic surface structures enables anisotropic transduction properties. The authors state, that the sensitivity with respect to normal and shear force depends on the shape of the silicone bumps.

Concluding one may state, that the application of a macroscopic surface structure contributes to the mechanical conditioning of the applied load and enables the transduction of normal and shear forces. In addition, the results presented in literature point to the application of isotropic surface structures in order to avoid a dependency of the transduction characteristics of the angle of the indentation force. Therefore, for the design of an artificial skin for real-world application on a robotic system macroscopic surface structures with a hemispherical shape are recommended. The macroscopic surface structure is applied to concentrate the occurring indentation force to the areas over the taxels and thus not to deform the spaces in order to create a measurable signal. Applying the described strategy the minimum required force may be minimized as only the upper substrate over the taxels has to be deformed in order to create a measurable signal. Figure 3.53 depicts the working principle of the macroscopic surface structure. The indentation force is concentrated by the surface structure to a smaller projected contact surface area, thus the pressure acting upon the underlying taxels is virtually increased. This effect results in an increase of the initial sensitivity of the artificial skin.

In figure 3.54 a model of the tactile sensor is subjected to normal load. The resulting distribution of the elastic strain is depicted for the spacer separated sandwich foil without, figure 3.54(a) and with surface structure, figure 3.54(b). The goal of the applied surface structure is maximize the initial sensitivity of the resulting tactile sensor, therefore the pressure applied to the sensitive surface area of the sensors has to be maximized. The introduction of the surface structure results in a virtual increase of the pressure through the reduction of the contact surface area.

In order to facilitate the detection of incipient slip the surface of the macrostructural ridges is equipped with a microstructure, see figure 3.55. The introduced voids between the spacers can be utilized to propagate slip-induced vibration to the remote pressure acquisition elements proposed in section 3.3.1. The afore derived



a) b)

Figure 3.54: The introduction of surface structures minimizes the contact area. Thus, the applied force is concentrated towards the sensitive surface area of the tactile sensor. The principle of the concentration of the applied force is exemplified in the above simulation. Please note, that the material parameters applied for this simulation do not represent the material properties applied for the proposed artificial skin.

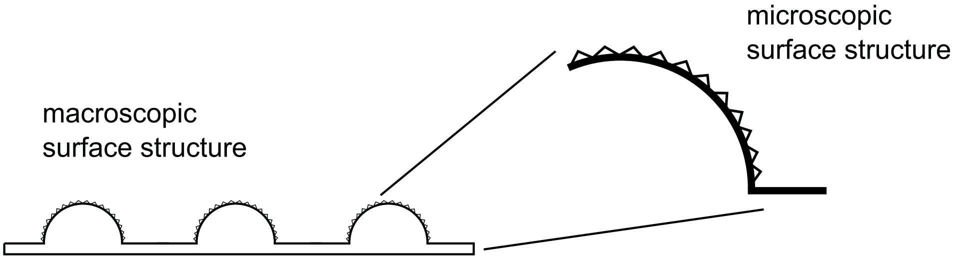


Figure 3.55: For the mechanical conditioning of relative sliding motion between an object and the surface of the artificial skin a combination of macroscopic and microscopic surface structuring is proposed. If the macroscopic surface structures are move over the surface of an object the individual macroscopic surface structures can independently slip over the surface and thus induce detectable vibrations. The microscopic structuring of the surface allows for the tuning of the frictional behavior of the overall surface.

solution of the spacer separated sandwich foil for the mechanical structure of the artificial skin contributes to the solution of the goal conflict between high sensitivity and required deformability. According to the proposed functional partitioning in the following a specialized damping layer for the dissipation of kinetic energy is derived.

Dissipation of kinetic energy in case of collisions With respect to the mechanical properties of tactile sensors Kerpa et al. [65] recommend that tactile sensors "should provide some mechanical damping behavior to protect the user in the case of a collision". Duchaine et al. [27] argue, that:

> "Most importantly, the skin should be able to absorb significant collision energy in order to provide mechanical safety [...]".

In order to determine which level of safety is required Povse et al. [122] evaluate the correlation between the energy density and perceived pain during robot-human collisions. The focus of the conducted study is to determine from subjective reports of human volunteers the pain level that is acceptable during pHRI. In contrast Park et al. [116] investigate the impact energy density and soft tissue damage. The authors propose a collision model to determine the elastic modulus of a mechanical damping layer to cover robotic systems. One may conclude from these studies, that irrespective of the focus on induced pain or resulting tissue damage a mechanical damping layer on top of the rigid cover structure of robotic system is beneficial with respect to the reduction of the collision severeness. Figure 3.56 depicts a set of dynamic indentation tests for the evaluation of the mechanical damping properties of a selection of polymer materials. For the evaluation of the damping characteristics

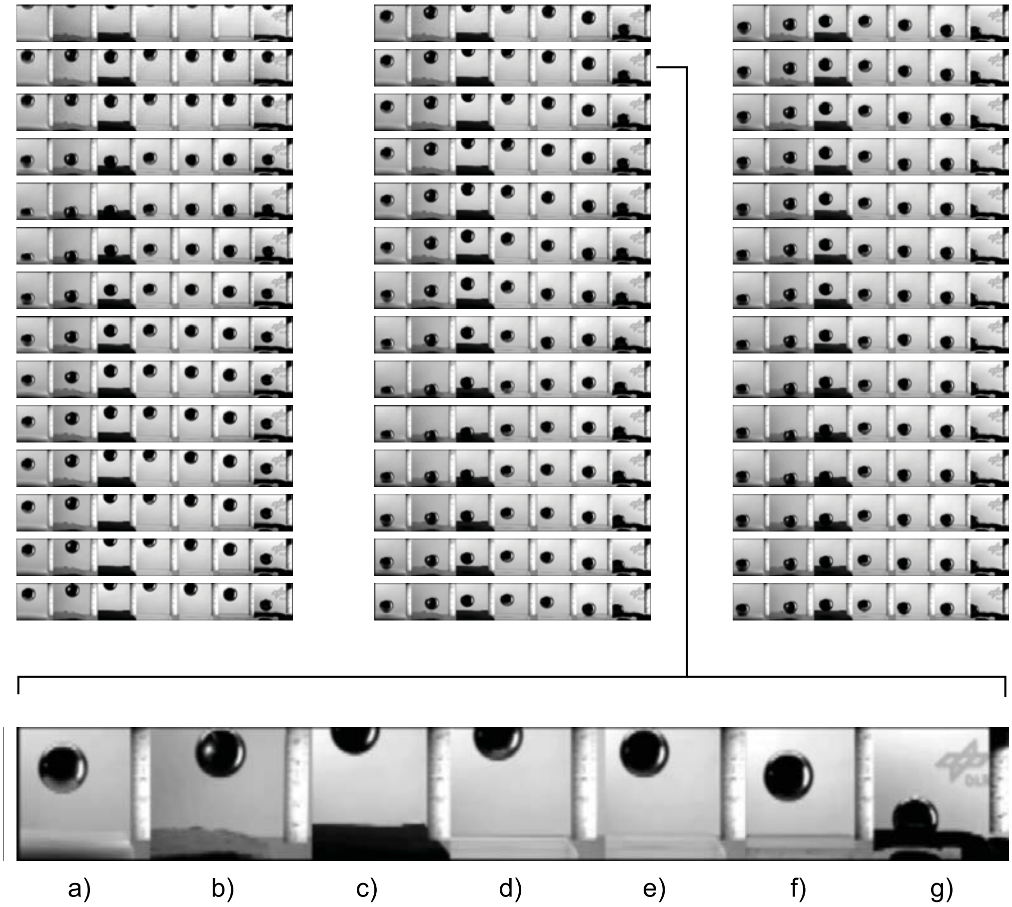


Figure 3.56: The three columns depict sequential high speed images of a dynamic indentation test for the selection of the material for the mechanical damping layer of the artificial skin. The high speed images are acquired at a frame-rate of 600 frames per second (fps), every fifth frame is depicted in the above figure. The following materials are analyzed: Open-cell polyurethane foam (a), closed-cell low density polyurethane foam (b), high density closed-cell polyurethane foam (c), silicone gels with varying Shore hardness (d-f) and a specialized damping material applied for protective sporting garments. Please note, that the exact material of specimen (g) was not disclosed by the manufacturer.

a test setup similar to the dynamic indentation test setup is proposed in section 4.1.2. For the tests metal ball bearing spheres ($20mm$ diameter) are applied. The spheres are fixated at a defined height above the surface of the specimen. Upon release the spheres are accelerated by gravity. The initial height upon release is $100mm$ above the surface of the specimen of the damping material. During the impact of the sphere with the specimen a fraction of the kinetic energy of the sphere is dissipated by the polymer material of the specimen. Specimen (a) and (b) consist of open-cell, (c) of a closed-cell polyurethane foam. Specimen (d-f) consist of capsulated silicone gel. Specimen (g) was obtained from a commercial crash pad for protective sporting garments. Please note, that the exact type of material of specimen (g) was not disclosed by the manufacturer of the crash pads. The combination of the height that the spheres reach after the initial impact and the time period until no more liftoff motion of the respective sphere can be observed in the high speed images characterizes the mechanical damping properties of the individual specimen. The detail still-frame at the bottom of figure 3.56 depicts the location of the spheres at the instant when the first sphere (subfigure g) comes to rest. It can be observed, that the damping properties of the materials (a-f) require longer time periods to absorb the kinetic energy of the dynamic impact of the spheres. Thus, it can be concluded, that with respect to the damping characteristics, material (g) exhibits the most favorable behavior.

Thermoregulation In order to enable a successful integration into a robotic system, the mechanical structure of an artificial skin has to provide a means of thermal energy dissipation. Figure 3.57 depicts the temperature distribution on the surface of robotic systems. The surface temperature of robotic systems, e.g. the DLR Justin, figure 3.57(a) is generally elevated with respect to the ambient temperature. Thermal energy is generated in non-ideal electric motors, friction affected gears, and power electronics, e.g. within the wrist of the DLR Justin, figure 3.57(b). Figure 3.57(c) depicts the temperature distribution in a robotic hand that is not actively moving. The temperature of the polymer based fingertips is only slightly elevated with respect to ambient temperature. Covering a robotic system with a polymer based artificial skin results in a thermal insulation of the robotic surface from the environment. Thus, the excess heat can not be dissipated as easily. Due to the high mechatronic integration observed in modern robotic systems only limited designed space within the robotic structure is available for the introduction of internal active cooling systems. Therefore, the covering artificial skin itself has to provide an active means of thermal energy dissipation. Based on the proposed functional partitioning a dedicated thermal management layer for the artificial skin

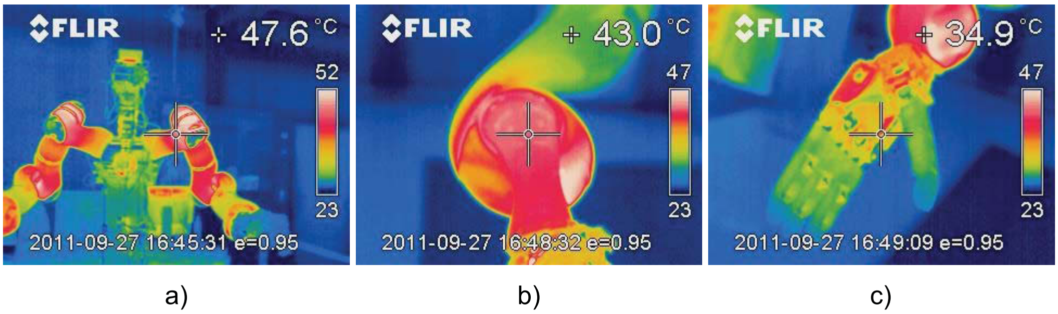


Figure 3.57: The surface of robotic systems depends on the activity of the robotic system and the site on the surface; subfigure a) depicts the temperature distribution of the DLR Justin after long term repetitive movement of the robotic arms, subfigure b) shows the wrist, subfigure c) the hand of the DLR Justin.

is proposed. The optimal location for the cooling layer is directly on the mechanical structure of the robotic system below the mechanical damping layer. Thus, the cooling layer can contribute to the dissipation of thermal energy without affecting the rest of the functionality of the artificial skin. In addition, this setup contributes to a collision tolerant design of the overall artificial skin as the cooling layer is located below the mechanical damping layer and thus is protected against indenting objects. Figure 3.58 depicts the concept of the cooling layer. Based on the same

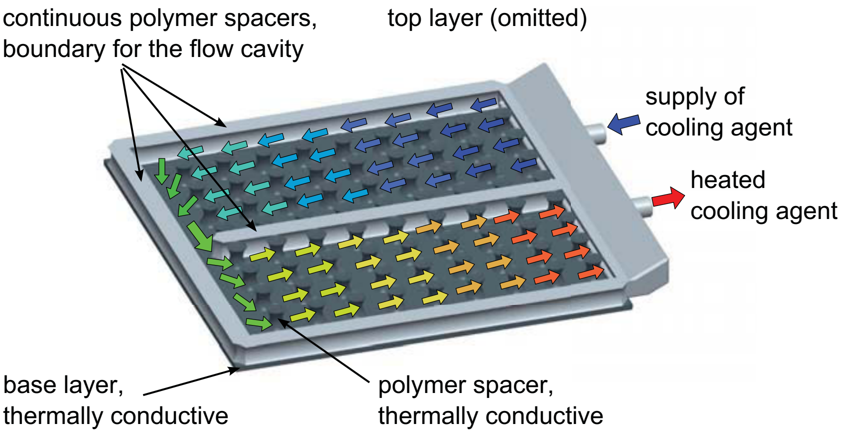


Figure 3.58: Thermoregulation based on material flux of cooling agent. For the cavity of the cooling cavity, a concept compatible to the desired layer setup of the artificial skin is proposed. The channels for the flux of the cooling agent are manufactured in the same way as the standard polymer based spacers, in contrast to the spacers in the sensitive layer the spacers of the cooling layer are continuous and thus form the boundary for the flow cavity.

concept as the mechanical structure of the superficial sensing layer, the cooling layer consists of a set of spacers introduced between two polymer foils. In order to enable the formation of cooling channels linear spacers are introduced to form the boundary of the sealed off cavity. The cooling channels can be filled with a fluidic of gaseous coolant. A forced circulation of the coolant enables the dissipation of the excess thermal energy from the robotic system. The proposed cooling layer thus contributes to a successful integration of an artificial skin into robotic systems.

Manufacturing process

The manufacturing process for the spacer separated sandwich foil can be divided in two subsequent steps. The preparation of the thin sheet polymer substrate and the subsequent bonding of two substrates with polymer based spacers. In order to enable the manufacturing of large area artificial skin the applied manufacturing processes need to be scalable. Therefore, no process e.g. based on spin-coating can be applied. Therefore, industry scale processes are evaluated for the manufacturing of the basic substrate. Standard industrial calendering processes allow for the preparation of silicone foil as thin as approximately $0.5mm$. If the thickness of the foils is to be further reduced the adhesion of the ready cured foil is likely to mechanically destroy the foil while detaching it from the rolls of the calander. Therefore, a preparation process is designed that allows for the continuous preparation of large area polymer substrate with a thickness of less than $0.5mm$. Figure 3.59 depicts the proposed manufacturing process. The processing consists of the dosing of the uncured polymer through a slit nozzle into the gap between the calander rolls. Applying a first set of non-heated rolls the uncured polymer is degassed and pressed into the desired thickness. Following, the uncured polymer is heated between a second set of calandering rolls. In order to complete the curing process the sandwiched polymer can be processed between heating plates (not depicted).

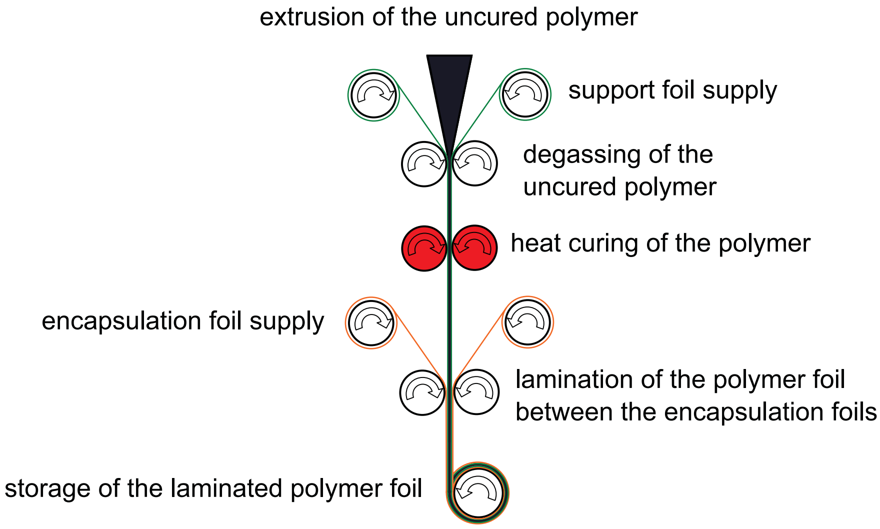


Figure 3.59: Based on the adaptation of the standard calandering process for the manufacturing of large area polymer foils a scalable manufacturing process of the basic polymer substrate for the mechanical base structure is proposed.

Depending on the length of the heating plates and the processing velocity the curing time can be adapted to the time required for the polymer of choice. Subsequent to the manufacturing of the basic polymer substrate a set of spacers is introduced e.g. via screen printing. Following the two prepared basic substrates are bonded according to the process depicted in figure 3.60(a-d). For a detailed description of the manufacturing process the interested reader may be referred to Strohmayr [155]. Within this patent application the manufacturing process of the spacer separated sandwich foil as a mechanical basic structure for an artificial skin is described in detail. The proposed manufacturing process allow for the production of large area artificial skin and thus supports the successful introduction into a robotic system.

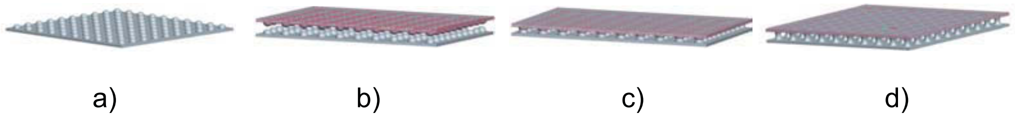


Figure 3.60: The manufacturing process of the polymer spacers is adapted from the packaging of integrated circuits where ball grid array chips are mounted upside down on the surface of printed circuit boards. The basic polymer substrate is provided with polymer dots with defined material volume, e.g. by screen printing (a). Subsequently two basic substrates equipped with polymer dots are opposed (b) and connected (c). Finally the polymer of the spacers is fixated (d).

3.3.3 Physical sensor interface

A major sticking point on the way towards an implementable artificial skin is the interface between the polymer based stretchable sensor and the metal based conductive tracks of integrated circuits of the readout electronics. Already Russell [128] identified the challenge of connecting polymer based to metal based conductive structures and proposed:

> "In order to remove the problem of making reliable electrical connections in an area subject to much bending and stretching both the strain sensors and the interconnecting wiring are formed from conductive polymer."

Based on this recommendation no rigid readout wires are introduced into the mechanically loaded area of the proposed artificial skin. Nevertheless this only relocates the problem of the interface between polymer and metal based circuit tracks. Commenting the work of Someya and colleagues, e.g. [152], LeMiex and Bao [87] state, that:

> "The transistors are wired together with the elastic interconnects to create the circuit, herein lies the challenging part, because fracture in flexible circuits due to strain occurs predominantly at the contact point or within the interconnect wire itself."

The authors refer the reader to the work of Lacour and colleagues, e.g. [76] who target their work to the development of stretchable conductive pathways. Lacour et al. [76] present an approach based on the metallization of stretchable substrates. According to the authors an electronic circuit based on the proposed approach can be stretched up to 12% without affecting the functionality of the circuitry. At strains exceeding 12% the presented stretchable metal conductive pathways fail. From the presented examples one may conclude, that not necessarily the conductive pathway itself but the mechanical and electrical connection to the rigid metal based circuit tracks is the weakest link. Most likely, the difference in elastic modulus between the polymer and the metal based readout circuitry causes the interface to fail. While a continuous change of elastic modulus would be optimal for the transition from polymer to metal no such material is known. Therefore, the attenuation of the physical hard-soft interface has to be based on the design of the geometric form of the metal based circuit tracks. Approaches based on meandering metal circuit tracks, e.g. by Gonzalez et al. [42] prove to be promising but the difference in elastic modulus between stretchable substrate and metal based meandering circuit track is still too sharp and causes the meander to fail under high or repetitive stretching.

In a study previous to this thesis tactile sensors based on the integration of metal readout wires in a polymer matrix material are analyzed, Strohmayr [158]. The experiments revealed that the integration of hard-soft-interfaces into the mechanically loaded area of tactile sensors poses additional challenges for the design of reliable sensors. Based on these findings a basic strategy for the design of interfaces between hard and soft materials for tactile sensors can be defined. The interface between metal conductor and polymer based conductor has to be attenuated. As an analogon for the design of hard-soft interfaces the design of mechanically loaded adhesive bonded joints can be analyzed. General principles for the design are presented in Niemann [105] P.172 - P.181. According to Niemann, adhesive bonded joints allow for the implementation of mechanically stable interfaces with a uniform stress distribution, e.g. for a mechanical interface between metallic and non-metallic components. In general, a shearing load is preferred in order to prevent scalping. Therefore, the adhesive layer has to be applied in the direction of the predominant load direction. These basic design rules can be adopted for the design of hard-soft interfaces for artificial skin sensors. In addition to mechanical bonding the interface between metal conductors and polymer based conductors the electrical connection is vital for tactile sensor design.

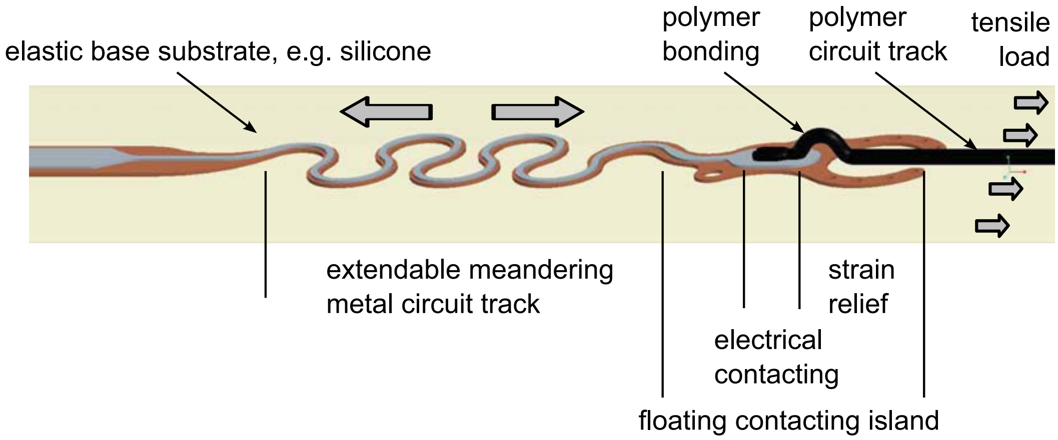


Figure 3.61: Attenuation of the hard-soft interface between metal readout wire (left) and polymer based circuit track (right). A tensile load results in the extension of the meandering metal based structure. In addition the contacting island is deviated according to the deformation of the underlying polymer base substrate, the contacting island "floats" on the polymer substrate.

Concept

Carta et al. [14] present the implementation of a demonstrator circuitry that shows, that an electronic circuit based on multiple islands that are connected via a meandering metal based interconnecting structure is operable. The authors report a relative elongation up to 78% for the meandering structures that connect the islands bearing the rigid components of the electronic circuitry. The presented approach is adapted for the design of the hard-soft interface. The challenge of

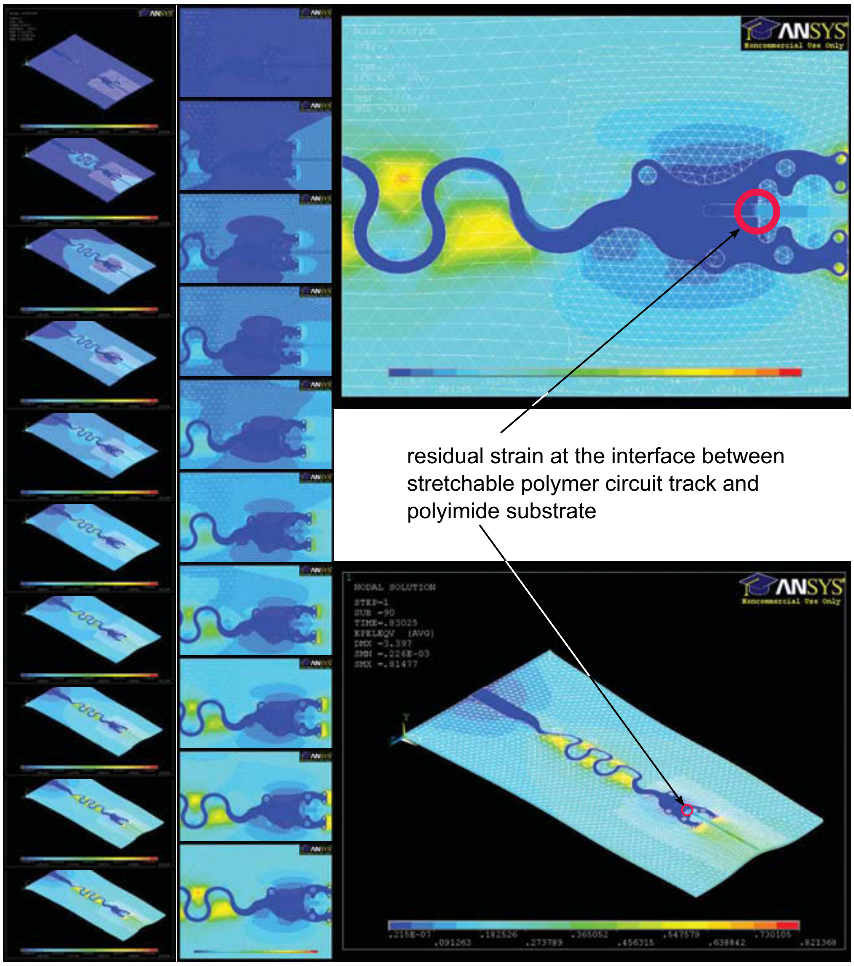


Figure 3.62: FEM simulation of the hard-soft-interface under tensile stress. The left collum shows the reaction of the hard soft interface if the basic polymer substrate is elongated, the polyimide substrate is bonded to the stretchable polymer substrate. The subfigures on the right demonstrate the residual stress in the polymer circuit track at the interface from stretchable (soft) basic substrate to the polyimide based floating island. Please note, that the simulation is based on a simplified setup that excludes the metal contacting wire on top of the polyimide substrate. A further simplification is the model of the material of the elastic substrate (Neo-Hookean). Therefore, the results of the simulation are indented as qualitative model to exemplify the working principle of the floating contacting islands.

the transition from the elastic PBCT towards the rigid metal circuit tacks is met as follows. There are three basic principles applied for the solution. Firstly the mechanical connection and the electrical connection are spatially separated. Secondly the electrical and mechanical contacting takes place on so called floating contacting islands which are able to move with the stretchable polymer substrate. Thirdly, the residual strain at the hard-soft interface is bridged by a so called polymer bonding approach. Figure 3.61 depicts the functioning principle of the floating contacting islands that enable a gradual elimination of the strain resulting from the elastic elongation of the flexible polymer substrate. Therefore, the floating island is equipped with two extensions forming a zone where the strain gradually decreases. In order to demonstrate the working principle of the floating contacting islands a FEM simulation is conducted. Figure 3.62 depicts the results of the simulation. The detailed subfigures on the right reveal a residual stress concentration at the transition point where the PBCT is routed from the stretchable substrate onto the floating contacting island. Figure 3.63 depicts a photograph of a prototype of the floating contacting islands based on a flexible printed circuit board. In order to further minimize the influence of the mechanical stress in the contacting area the transition from stretchable substrate to rigid metal contacting area is adapted from the packaging of integrated circuits. Based on metal (mostly Gold) wires the die is connected to the contacting pads of the overall chip via the so called bonding process. This approach is adapted for the hard-soft interface between PBCT and metal readout circuitry. At the transition point, i.e. the area where the PBCT leaves the surface of the elastic substrate and is placed on the surface of the comparably rigid flexible PCB the PBCT is routed in a free standing arc that spans the transition point, see figure 3.64. According to the proposed spatial separation, the mechanical connection is implemented within the strain reduction zone. Therefore

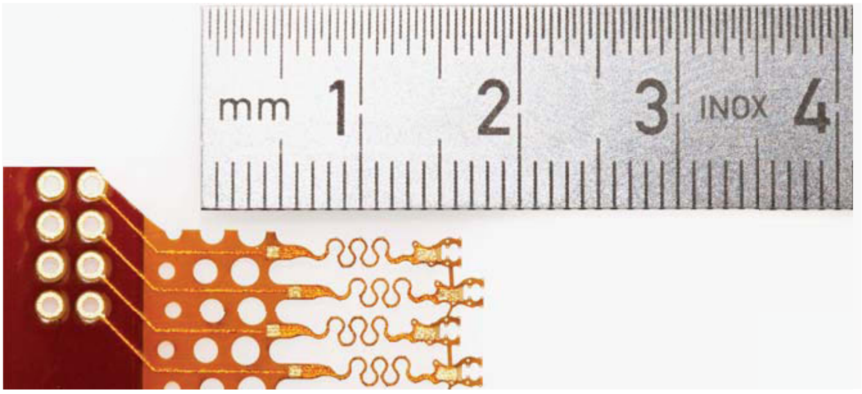


Figure 3.63: Floating contacting islands

the electrical connection is implemented by polymer bonding of the PBCT onto the electrical contacting surface on the floating island. The interested reader may be referred to [157]. This patent application describes in detail the setup and functioning principle of the floating contacting islands as a means for the solution of the challenge of the hard-soft interface between polymer and metal based circuit tracks. The manufacturing of the floating contacting island can be based on the standard processes of industrial manufacturing of flexible printed circuit boards. For the implementation of the polymer bonding the direct extrusion printing process proposed in section 3.3.1 can be applied. Figure 3.65 depicts one of the first prototypes of a hard-soft interface based on the proposed direct extrusion printing process.

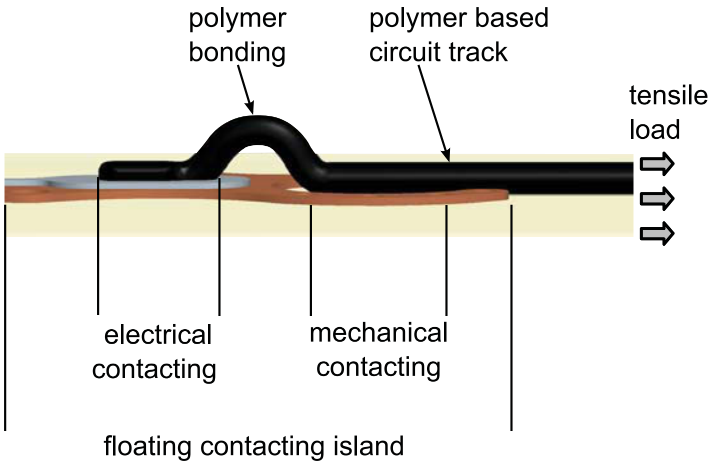


Figure 3.64: The residual relative movement of the polymer based circuit track and the floating contacting island can be dissolved in an polymer arc (polymer bonding). Through the combination of floating contacting island and polymer bonding the electrical contacting area is freed from mechanical load.

Figure 3.65: Prototype of the hard-soft interface based on polymer bonding of a PBCT onto a floating contacting island.

3.4 System integration

Within this section the development of a scalable tactile surface sensor for the application on robotic systems is presented. Exemplarily, a tactile surface sensor for the acquisition of normal forces is described. The goal is a set of prototypes that exemplifies that the design paradigms derived in section 3.2.7 enable the implementation of a tactile surface sensor that can be scaled with respect to sensor surface area and spatial resolution.

3.4.1 A scalable tactile surface sensor

A stretchable and thus collision tolerant tactile surface sensor is developed based on the design paradigms proposed in section 3.2.7. The tactile surface sensor as central element of an artificial skin for robotic systems is based on the combination of the functional components derived in section 3.3. The functionality of the transduction principle is demonstrated for a normal force acquisition sensor. Following the proposed design paradigms an all-polymer tactile surface sensor is implemented, that avoids rigid elements within the mechanically loaded sensor area. Hence the resulting sensor prototype can be fully compressed without being mechanically damaged. To solve one of the most prominent challenges on the way from "classical" tactile sensors towards an implementable artificial skin a collision tolerant design has to be combined with the required high initial sensitivity of the sensor system. The combination of the functional components derived in section 3.3 leads to a tactile surface sensor that is able to unite an overload proof, collision tolerant design with the required high sensitivity. Two strategies, derived in section 3.2.7

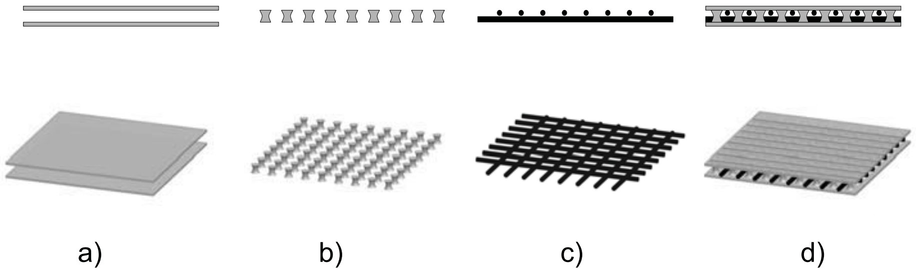


Figure 3.66: The tactile surface sensor consist of the following functional components: Two polymer foils (a), a set of polymer based spacers (b) that mechanically fixate the two polymer foils. Two orthogonal sets of polymer based circuit tracks (pbct) (c) are applied as readout wires while at the same time providing the desired transduction properties of the tactile surface sensor. Sub-figure (d) depicts the integrated tactile surface sensor.

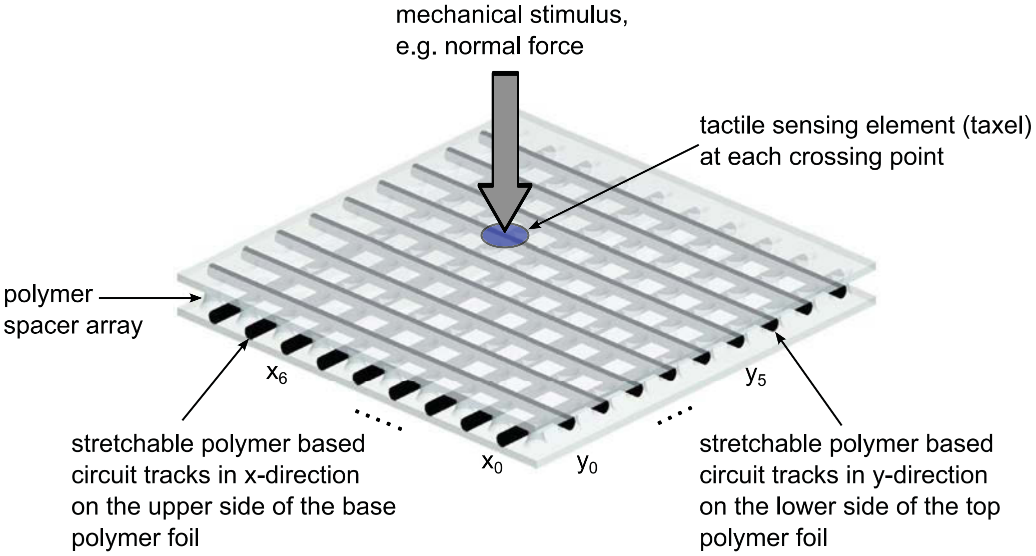


Figure 3.67: The working principle of the tactile surface sensor is based on two sets of polymer based circuit tracks (PBCT). The PBCT are arranged in two orthogonal sets that consist of an adaptable number of parallel PBCT. At each crossing point a sensitive area (taxel) is formed. The mechanical base structure of the tactile surface sensor encloses the two intersecting sets of PBCT. The sets are mechanically fixated to the two polymer foils of the spacer separated sandwich foil. The upper set of PBCT is mechanically fixed to the bottom side of the upper polymer foil, the lower set of PBCT is fixed to the upper top side of the bottom polymer foil. The two polymer foils are mechanically fixated to each other via polymer based spacers.

are applied in order to increase the initial sensitivity of the sensor setup. Firstly, the initial sensitivity of the tactile surface sensor is increased by reducing the polymer volume that has to be deformed to evoke a measurable sensor output. The volume reduction is based on the introduction of geometrically defined voids into the sensor setup. The tactile surface sensor is therefore composed of a spacer separated sandwich foil, see figure 3.67. In order to further enhance the initial sensitivity the sensing elements are introduced into the geometrically defined voids. The scalable tactile surface sensor is composed of the spacer separated sandwich foil as basic mechanical structure and two orthogonal sets of polymer based circuit tracks that have been developed in section 3.3. The basic mechanical structure is composed from two polymer foils, figure 3.66(a), that are separated by polymer spacers, figure 3.66 (b). The taxels of the tactile surface sensor are composed of two sets of polymer based circuit tracks, figure 3.66(c). The individual sets are arranged in two spatially separated layers. The result of the combination of the functional components is an entirely polymer based stretchable multilayer printed circuit board that enables the transduction of normal forces based on an conformable array of taxels, figure 3.66(d). The polymer based spacers enable the mechanical fixation of the two polymer foils. In addition the spacers provide the restoration force that is required to separate the PBCT of a taxel after an external load is removed. Moreover, the spacers bear the mechanical load that results from external shear forces and prevents the dislocation of the two polymer foils and thus enables a stable arrangement of the individual taxels. Independent of the form of an underlying mechanical damping layer the polymer based spacers secure the separation of the PBCT in absence of an external load. Thus, a defined off-state of the tactile surface sensor can be achieved. The functional principle of the proposed tactile surface sensor is described in the patent application of Strohmayr [156].The second strategy for the increase of the initial sensitivity is to endow the sensor surface with a macroscopic surface structuring that conditions the mechanical stimulus towards the sensitive areas of the tactile surface sensor. A FEM simulation of the behavior of an artificial skin surface with and without macroscopic surface structure is conducted in Krauß [73]. Following the results are summarized. Figure 3.68(a) depicts

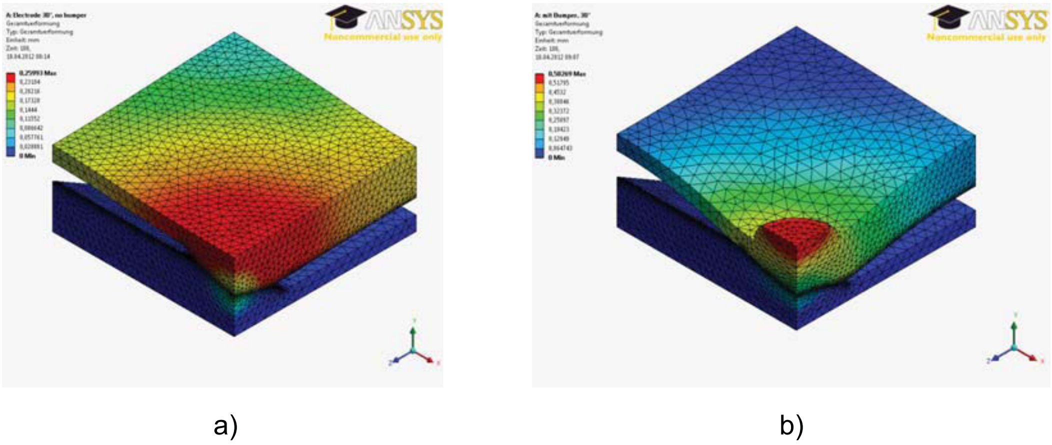
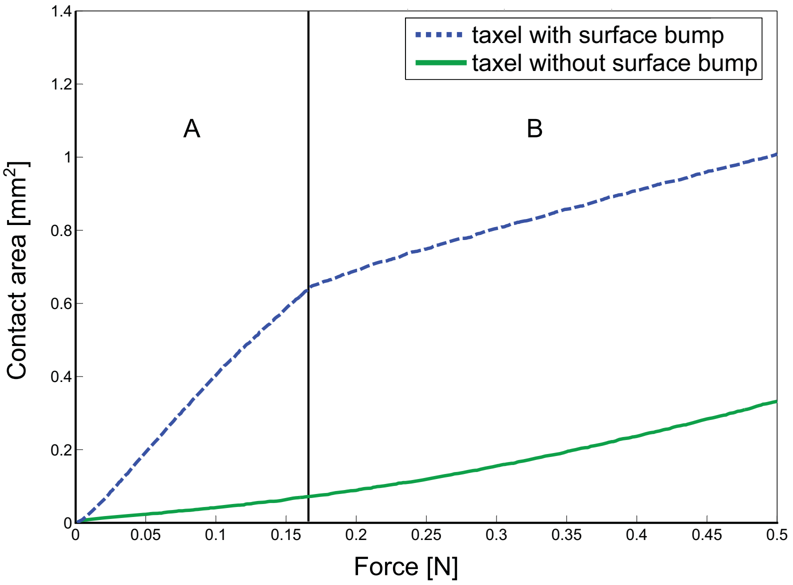
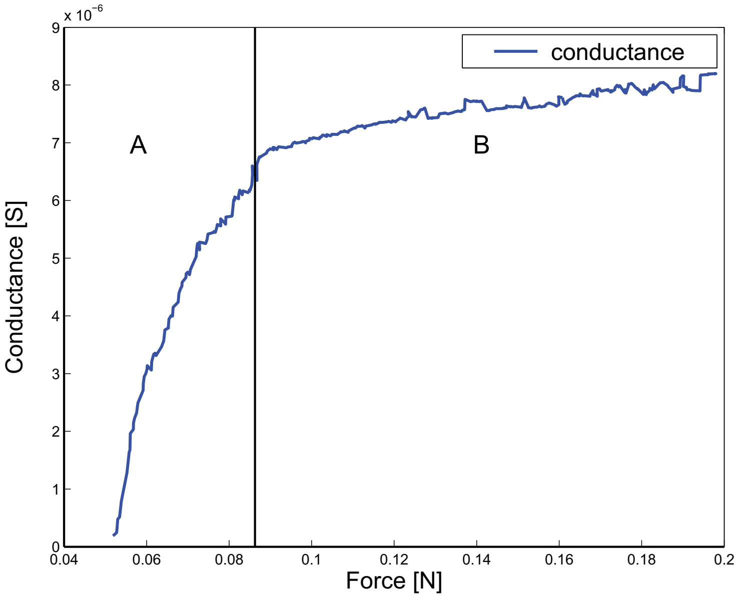


Figure 3.68: The simulation of the behavior of the combined functional components shows, that the introduction of the macroscopic surface structure greatly affects the transduction properties of the tactile surface sensor, figure adapted from Krauß [73]

the effect of an external normal indentation force, applied to a single taxel without surface structure. The introduction of a surface structure, results in an concentration of the indentation force towards the sensitive area directly above the taxel, figure 3.68(b). Thus, the available indentation force is projected to a smaller contact surface area and the applied pressure is virtually increased. A figure depicting the individual simulation steps is presented in the appendix, see figure 3.54. The analysis of the relation between the indentation force and the resulting changes in the contact surface area between the intersecting PBCT of the taxel is depicted in figure 3.69(a). The dashed curve represents the transduction behavior with applied surface structure. Clearly two regions can be distinguished. In region ’A’ the indentation force acts solely of the surface structure, thus a high initial sensitivity can be observed. As soon as the surface structure is completely indented the indentation force acts upon the entire surface area of the taxel. Depending on the height of the surface structure the force required for the complete indentation of the surface structure can be adapted. The underlying spacers contribute to the reaction force countering the external normal indentation force, in region ’B’ and thus a further increase of the external indentation force results in a smaller change in the contact surface area. Thus, the sensitivity is decreased and enables an increase of the dynamic range of the taxel. Figure 3.69(b) exemplarily depicts the acquired electrical conductance of the tactile surface sensor prototype for a quasi-static indentation of a single taxel. The quasi-static indentation tests have been conducted and described in detail in Leupolz [89]. The diameter of the cylindrical indentation probe is $2mm$. The graph depicted in figure 3.69(b) illustrates the feasibility of the implementation of a taxel with high initial sensitivity (region ’A’) and a wide dynamic range (region ’B’).



(a) The introduction of a surface structure results in an increase of local pressure in the sensitive area of the taxel and thus enhances the sensitivity of the tactile surface sensor in region 'A'. In region 'B' the surface structure is completely indented and the external indentation force is exerted on a larger surface area; Figure curtesy of Krauß [73]



(b) The response of the tactile surface sensor prototype for a quasi-static indentation of a single taxel. Test conducted on the testbed developed in Leupolz [89]; Figure curtesy of Leupolz [89]

Figure 3.69: Transduction properties of the combined functional components. Subfigure (a) depicts the results of a FEM analysis. Subfigure (b) depicts the transduction properties of the implemented tactile surface sensor prototype.

3.4.2 Materials and methods

Taking into account the future integration of the tactile surface sensor as a whole-body touch sensitive cover for an entire robotic system the implementation of the tactile surface sensor is based on manufacturing processes that enable the scaling of the resulting sensor prototype. For the implementation the manufacturing processes proposed in section 3.3 are applied. Therefore, in the following the applicable polymer materials are selected according to their fitness for the proposed manufacturing processes. Standard industrial polymer processing technology often involves batch sizes of hundreds of kilograms and thus can not directly be scaled down to the small polymer volumes that are required for the manufacturing of an artificial skin. Therefore, a specialized micro-scale polymer processing technology is developed in Pfeiffer [121]. To form the polymer based circuit tracks an adaptive extrusion printing technology that enables the manufacturing of tactile surface sensors for 3D-curved surfaces is introduced, compare section 3.3.1.
The control of the manufacturing process of the PBCT enables the tuning of the desired transfer function of the resulting taxels to the requirements of the intended application site. The design of the nozzle of the printer affects the shape of the PBCT and thus contributes to the transduction principle. Consequently, the utilized polymer base materials are selected in order to allow for the implementation of the proposed manufacturing processes. The development of polymer materials that exhibit the desired electrical and mechanical properties is based on the finding of the development of the functional components in section 3.3. The proposed manufacturing, e.g. the formation of the desired cross section of the PBCT during the extrusion printing requires a structural viscosity of the polymer material. Therefore, the application of an uncured polymer material with high viscosity is proposed. In order to meet the requirements according to Harmon [50] the materials applied for the implementation of the tactile surface sensor have to be mechanically flexible, conformable and stretchable. Therefore, the application of elastomers as basis material for tactile sensors is most promising.

Material The desired stretchability of the tactile surface sensor requires the application of stretchable electrically conductive circuit tracks. With respect to stretchable conductive circuit tracks Lacour et al. [76] state, that:

> "Conformable electronic surfaces require electrical conductors that are fully elastic and have a resistivity as low as that of metals. Currently, conductive rubbers – silicones filled with carbon or silver particles – are among the few materials that are both mechanically elastic and electrically conductive. However, they present high electrical resistivity that

> may change significantly under stretching, leading to poor interconnect performance and reliability".

The electrical conductivity of polymer compounds can be increased by incorporating electrically conductive particles into a polymer matrix. The electrical conductivity of the particle filled polymer matrix is highly dependent of the applied filler content. Wessling [178] proposes a model for the electrical conductivity of carbon black filled polymer material. The author states, that the nonlinearity of the relationship between the ratio of the added filler material and the polymer matrix can be explained by a phase transition of the arrangement of the carbon black particles. According to Wessling, the transition from dispersed to flocculated phase can describe the non-linear change in electrical resistivity. The addition of rigid particle into the compliant polymer matrix not only affects the electrical conductivity of the resulting filled polymer but also alters the mechanical properties of the filled polymer. In general the addition of filler particles increases the tear strength and at the same time reduces the elongation at break. Princy et al. [124] conclude from their study on conductive silicone rubber compounds:

1. "The resistivity of the composites that contain carbon blacks like acetylene black, lamp black, and ISAF black decreases as the carbon black concentration increases.
2. The mechanical properties like tensile strength, tear strength, and elongation at break decreases, and hardness increases as the amount of carbon black increases.
3. Resistivity increases on heating and decreases on cooling in the case of acetylene black and lamp black. For ISAF black, resistivity first increases and reaches a maximum at 80°C, and then decreases on heating and also decreases on further cooling.
4. The area of the hysteresis loop during the heating–cooling cycle depends on carbon black concentration."

With increasing filler content the undisturbed volume of the polymer surrounding the particles decreases. Hence less polymer results in decreasing elasticity of the filled polymer. Thus, the content of the filler particles can not be arbitrarily increased. These effects create a conflict of goals as high electric conductivity is required but at the same time the elasticity of the resulting polymer compound is essential for the later integration into robotic systems. Following the required material properties for the sensory elements are outlined. The design of the sensory cells requires the manufacturing of stable polymer printed circuit paths that can be handled without melting away. Therefore, only polymers can be applied that exhibit a structural viscosity, i.e. that are paste-like at ambient pressure and temperature. The desired 3D shape of the printed electrodes prevents the application of pourable polymers, e.g. conductive inks. The application of thermoplastics would be desirable from a compounding point of view as e.g. twin-screw extruders allow for homogeneous dispersion of the conductive filler particles in the polymer matrix. The handling of a viscous high temperature polymer melt for manufacturing of tactile sensors would require the constant heating of the polymer melt and thus can not be applied for the proposed direct extrusion printing process.

Therefore, the application of a heat curing polymer compound, e.g. silicone is proposed. The effects of strain to the electrical resistivity of silicone filled with electrically conductive carbon black particles are investigated e.g. by Kost et al. [71]. With respect to the application of carbon black filled silicone polymer a strain dependency of the electrical resistivity is observed. While a mechano-resistive behavior is e.g. desired for the strain sensing elements, a dependency of the volume resistivity of the PBCT acting as readout wires is undesired. This is because not only the mechanical loading of the sensitive element but also the elongation of the elastic contacting wires results in an increasing electrical resistivity and thus the reliability of the derived tactile information is reduced. Therefore, the influence of mechanical loading on the electrical conductivity of the conductive polymer has to be minimized. There are multiple approaches towards the minimization of the resistive effects within polymer compounds under mechanical loading. The first approach is based on the reduction of the elongation of the PBCT due to mechanical loading e.g. through a meandering structure of the PBCT. This results in an increased overall length of the PBCT entailing an increase of the overall electrical resistivity of the PBCT. In order to avoid these effects, the mechano-resistive behavior of the polymer compound has to be reduced in order to enable electrically highly conductive PBCT.

The combination of particles with different average particle size is proposed by Cheng et al. [16] who disperse copper powder (average particle size $50 \mu m$), carbon black (average particle size $35 nm$) and silver powder (average particle size $25\ nm$) in silicone. The authors apply a process based on the addition of cyclohexane to reduce the viscosity of the silicone during the mixing process. The cyclohexane is removed from the compound prior to the mold process. The authors report an electrical resistivity of a single taxel to change from $10 M\Omega$ (no pressure applied) to $5 k\Omega$ (taxel mechanically loaded with $700 kPa$). While the reported mechano-resistive behavior is desired for the transduction of mechanical load to a change in electrical resistivity, it is undesired for the design of PBCT. In addition the minimum reported electrical resistivity is too high for the application in PBCT. Moreover, the high overall filler content of approximately $40\%w/w$ is likely to result in a low extensibility of the resulting cured silicone compound. Thus, the proposed approach based on the combination of different particles with different scale of the average particle size can not directly be utilized for the design of PBCT. Nevertheless the basic idea of this approach can be adapted to the challenge of the minimization of the mechano-resistive effect. Therefore, the principle of the multiple filler particles is adopted for this thesis.

Next to the concentration and the size of the applied particle, the morphology of the particles is crucial for the electrical conductivity of the resulting filled polymer material. The basic idea is the formation of a micrometer-scale 3D network of electrically highly conductive particles. Figure 3.70 depicts the basic principle. If a PBCT based on spherical particles, figure 3.70(a), is elongated, figure 3.70(b) the point contacts between the individual particles are disturbed. This effect results in a dependency of the electrical conductivity of the PBCT from the elongation of the PBCT. In order to avoid this undesired effect, instead of spherical or flake-shaped particles, the application of terete particles is proposed. In addition, the terete particles are axially oriented, figure 3.70(c). The basic idea is that a comparatively constant volume resistivity can be achieved through a parallel sliding contact between the particles in the case of an axial elongation of the PBCT, figure 3.70(d).

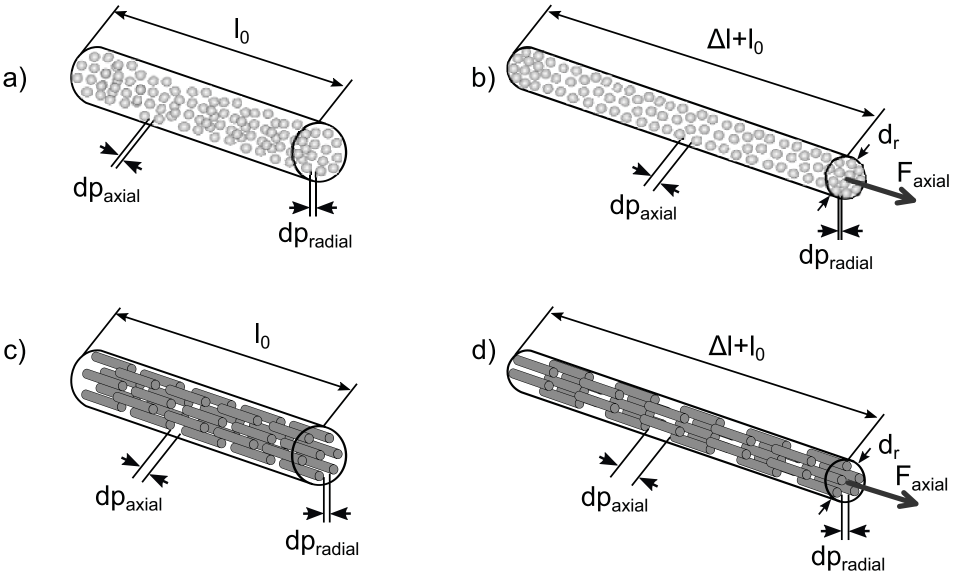


Figure 3.70: Reduction of the strain dependency of the electrical volume resistivity by the application of electrically conductive particles with terete aspect ratio

To enhance the electrical conductivity even further the terete particles are not incorporated into an insulating polymer matrix but into a polymer matrix filled with electrically conductive nano-particles. Therefore, a combination of nanometer- and micrometer-scale particles is incorporated in a polymer matrix. This hybrid filler system is based on the combination of different fillers and their distribution in the polymer matrix. The proposed axial orientation of the terete particles can be obtained through the utilization of rheological phenomena during the direct extrusion printing process. Gradients in flow velocity are exploited in order to orient the terete particles within the PBCT. Figure 3.71 depicts the working principle of the in-line orientation of the terete particles during the direct extrusion printing process. This approach enables the manufacturing of electrically highly conductive PBCT with a reduced mechano-resistive behavior. Extrusion experiments have shown, that the addition of solvents results in polymer compounds that exhibit a pronounced structural viscosity due to the required high concentration of filler particles. In combination with an increased pressure difference the deposition process can not be controlled properly. A relative change of only $50Pa$ changes a paste-like polymer compound into a low viscosity fluid, preventing the adaptation of the required nozzle positioning velocity. Therefore, the application of solvents for viscosity reduction of particle filled polymer compounds is not to be recommended. Hence an alternative approach enabling the solvent-free processing of the polymer

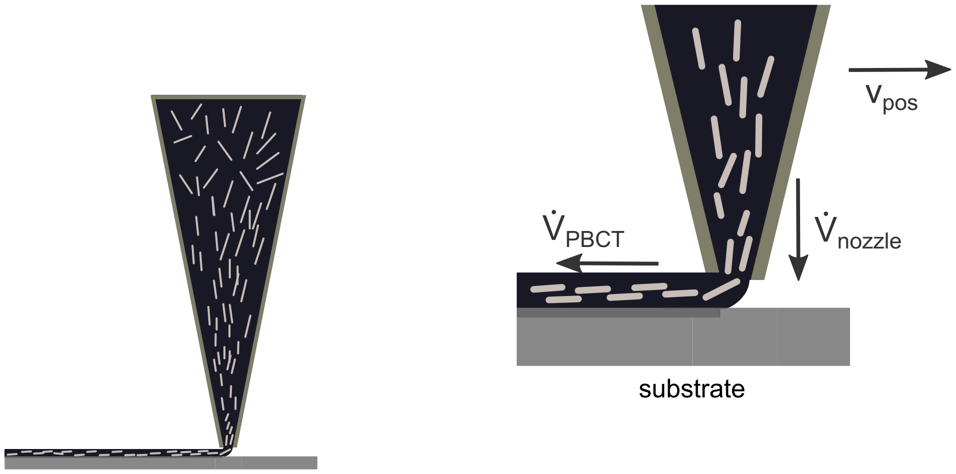


Figure 3.71: Principle of the inline manufacturing process of the PBCT with an anisotropic volume resistivity

compounds is proposed in Pfeiffer [121]. Following the approach towards a micro mixing technology for highly viscous polymers is outlined accordingly.

Micro mixing of highly viscous silicone

The standard mixing procedures of highly viscous polymers in industry involve thousands of kilograms per batch and require huge machinery. For the application in artificial skin only small material quantities in the order of grams are required at one time. The processes and apparatuses of the polymer processing industry can not directly be scaled down to single grams per batch therefore in Pfeiffer [121] a micro mixing system for highly viscous polymers is developed, figure 3.72 (a). The main objective of the mixing process is the uniform mixing of the different polymer components. Due to the high viscosity no turbulent mixing process can be applied. Therefore, a mixing based on laminar flow phenomena and diffusion processes in the polymer compound are investigated. The effect of the reduction of the aspect ratio of carbon fibers during the mixing into nitrile rubber is described by Pramanik et al. [123]. According to the authors the aspect ratio of the applied carbon fibers is reduced during the mixing process as a result of the shear forces exerted to the fibers. Therefore, the general objective of the design of a mixing process is to thoroughly mix the two polymer components and at the same time keep shear forces

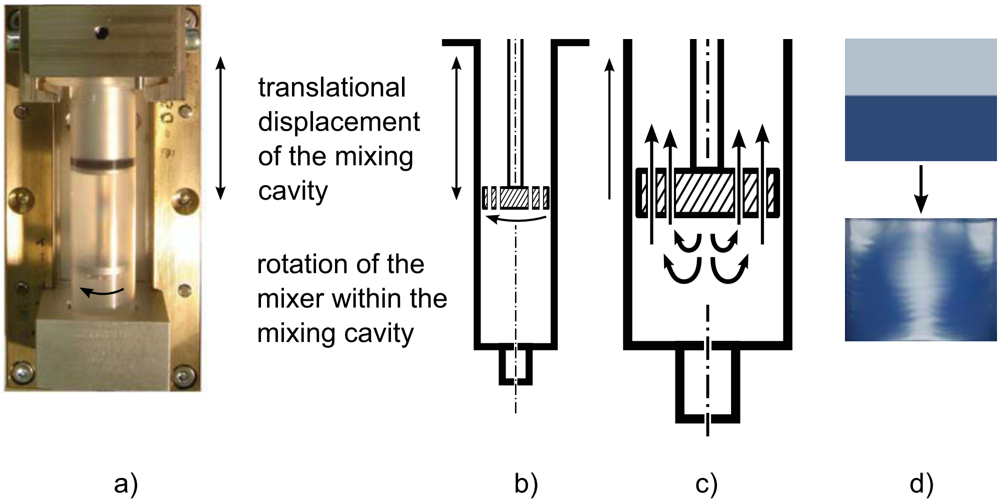


Figure 3.72: Micro scale mixing of highly viscous polymers based on the mixing principle of H. Nieländer [104], figure adapted from Pfeiffer [121].

within the polymer compound as low as possible in order to avoid the reduction of the aspect ratio of the introduced fibers. Therefore, the mixing principle proposed in the patent application of Nieländer [104] in 1970 is applied. The micro mixing system implemented in Pfeiffer [121] is based on the synchronous translational displacement of the mixing cavity and the rotation of the mixer within the cavity, figure 3.72(b). During the mixing process the polymer material is displaced and flows through the voids in the rotating mixer. The thickness of the layers of the components of the polymer is reduced in order to allow for the mixing of the polymer components based on diffusion processes, figure 3.72(c). Figure 3.72(d) exemplifies the mixing of the two polymer compounds, unmixed (top) and partially mixed (bottom). The main objective of the micro mixing process design was the minimization of dead volumes and the resulting material loss. Hence the mixing has to take place in a cavity that can is applied throughout the polymer processing. The quality of the mixing process based on different mixing strategies and different mixing elements is investigated by Pfeiffer [121]. Based on these results a reliable and reproducible mixing process for the applied silicone could be implemented. This mixing process is the basis for all subsequent manufacturing steps of the proposed polymer based artificial skin.

Fillers and their distribution in the polymer matrix

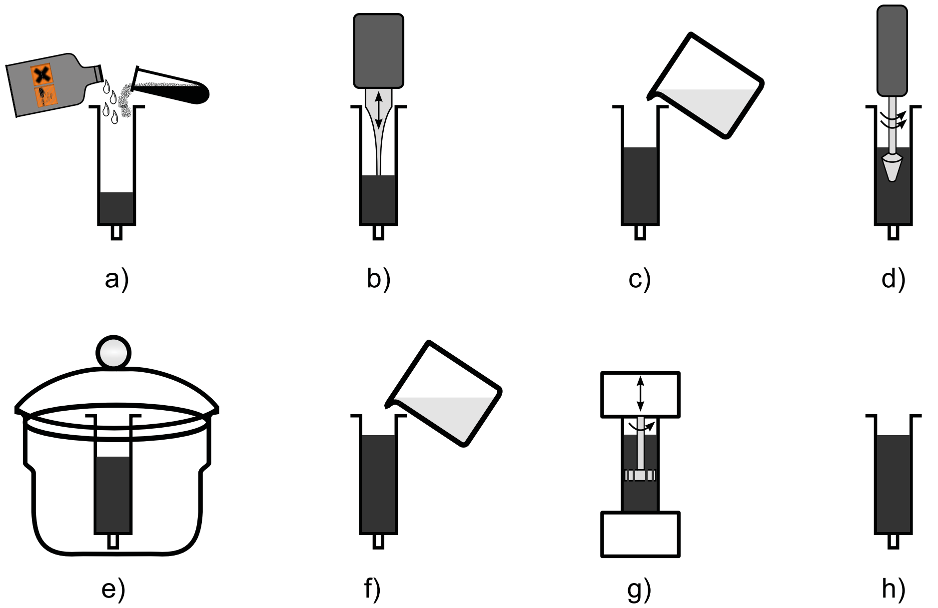


Figure 3.73: For the dispersion of particles in highly viscous polymers the following process is proposed.

The dispersion of particles in a highly viscous polymer matrix is based on the principle manufacturing process depicted in figure 3.73. The first step is mixing of the liquid solvent with the powder of the nanometer particles, e.g. carbon black (XC72 Cabot®, [41]), figure 3.73 (a). In order to avoid a premature curing of the resulting compound, as a result of an increase of temperature in the polymer compound during the mixing process. Subsequently the particle aggregates are de-aggregated via ultrasound induced vibration, figure 3.73(b). Following, a defined volume of a pre-mixed polymer compound (e.g. components A and B of a two component heat curing silicone, pre-mixed according to Pfeiffer [121]) is added, figure 3.73(c). Then, the resulting low viscous solution is mixed applying a high speed mixer, figure 3.73(d). The resulting homogeneous dispersion is degassed and the volatile solvent removed from the dispersion, e.g. via a vacuum in an exsiccator, figure 3.73(e). The product, a highly viscous polymer compound is utilized as a master-batch. By adding defined volumes of unfilled polymer, the desired particle concentration can be obtained, figure 3.73(f). Finally, the highly viscous polymer is thoroughly mixed according to the process proposed in Pfeiffer [121], figure 3.73(g), to obtain the polymer compound with the desired electrical and mechanical properties for the extrusion printing process, figure 3.73(h).

3.4.3 Prototypes

For the evaluation of the proposed design strategy and the required manufacturing processes a set of prototypes of the tactile surfaces sensor is implemented. In order to demonstrate the scalability of the spatial resolution three different types of prototypes with different spatial resolution are manufactured. The spatial resolution of the prototypes ranges from $1.25mm$, depicted in on the left in figure 3.74 to $2.5mm$ depicted on the right. The suitability of the manufacturing processes for the implementation of large area tactile surface sensors is demonstrated with the manufactured 40×40 taxel array. The resulting 1600 taxels enable a spatial resolution of $2.5mm$, figure A.4 in the appendix depicts the assembled prototype. In order to demonstrate the adaptability of the proposed design approach a large area tactile surface sensors is implemented. The manufactured prototype forms the basis for a whole-body touch sensitive cover for entire robotic systems. Figure 3.75 depicts one of the first prototypes of the large area tactile surface sensor. Figure 3.76 depicts a tactile surface sensor prototype with 5×8 taxels and a spatial resolution of $20mm$ for large surface areas. The photograph illustrates the ability of the tactile surface sensor to be integrated on top of a mechanical damping layer and cover the complex 3D-curved geometry of the covering structure of a DLR LWR III.

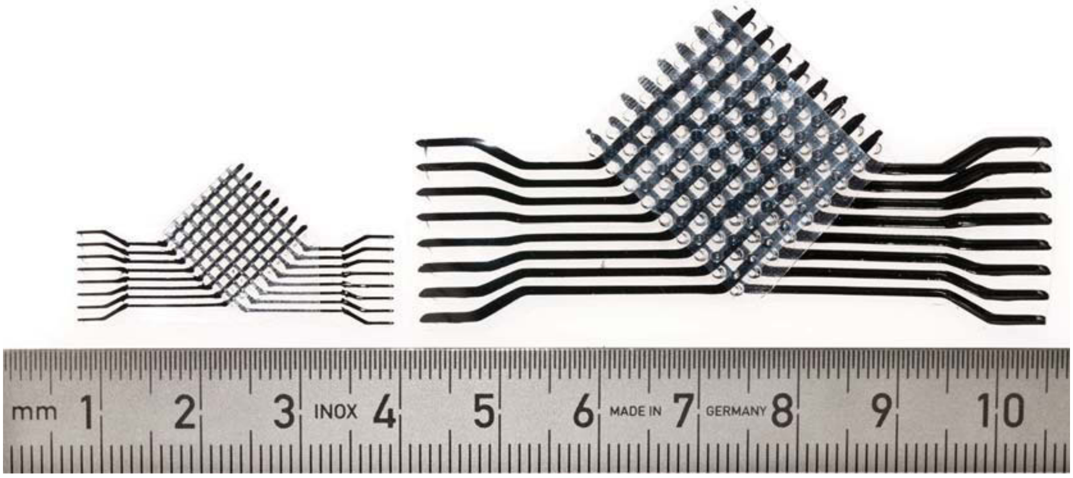


Figure 3.74: Prototypes of the scalable tactile surface sensor of the artificial skin. The sensor on the left provides a spatial resolution of $1.25mm$, e.g. for the equipment of robotic fingertips. The sensor prototype on the right provides a spatial resolution of $2.5mm$, e.g. for the palms of robotic hands. The figure illustrates the scalability of the proposed sensor design and the underlying manufacturing processes.

Readout electronics For the evaluation of the properties of the proposed tactile surface sensor a dedicated readout electronics is designed in Schnös [135] and re-

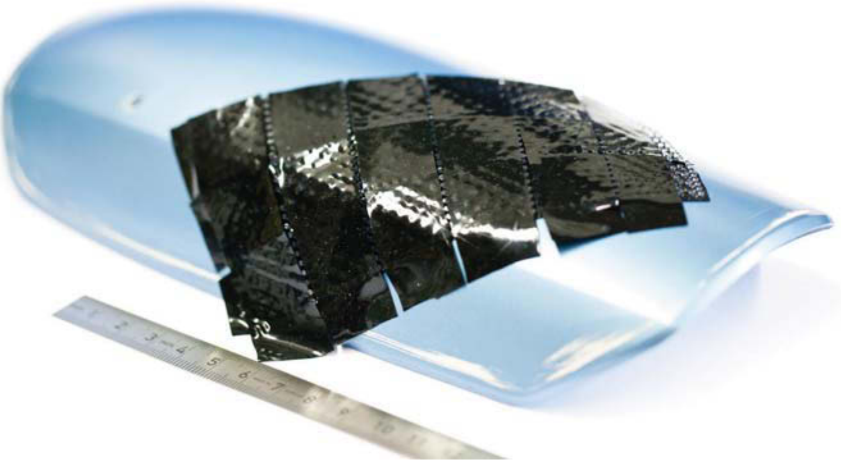


Figure 3.75: Prototype of normal force acquisition tactile surface sensor with 3×5 taxels with a spatial resolution of $20mm$. The presented prototype is designed on order to cover a large surface area as the depicted covering structure of the DLR Hand-Arm-System (upper arm cover).

Figure 3.76: Front and side view of a prototype of a normal force acquisition tactile surface sensor with 5×8 taxels. The spatial resolution of the prototype is $20mm$. While the spatial resolution is comparatively low, the design of the tactile surface sensor enables the reduction of the insensitive surface area. The sensitivity of the tactile surface sensor is independent of the location of a contact within the surface area of an individual taxel.

fined and supplemented in Schneider [134]. The performance of a tactile sensor system depends on the mechanical design of the sensor hardware and the applied readout electronics. In order to increase the performance of the tactile surface sensors a dedicated readout electronics is implemented. The readout strategy pursued in Schnös [135] is depicted in figure 3.77. The applied data acquisition strategy is based on the sequential addressing of individual taxels. Thus, the reaction time of the entire tactile sensor system depends on the number of taxels. The maximum scanning rate is defined by the number of taxels to be scanned. The physical properties of the readout electronics of the artificial skin sensor system restrict the scanning rate. Depending on the scanning rate the time required to ensure, that all taxels have been read out cumulates to the overall reaction time of the tactile surface sensor system. In order to reduce the reaction time and e.g. enable the initiation of active collision reaction strategies, the readout strategy proposed in section 3.2.6 is implemented in the readout electronics designed in Schneider [134]. To allow for the implementation, the hardware of the readout electronics has to be adapted. In practical, the multiplexers applied in Schnös [135] are replaced by analog switching matrices in the design of Schneider [134]. The basic idea for the optimization of the reaction time of the readout electronics is the supply of tactile information in a sequential manner. Based on the sequential increase of the information content a high speed sensor data processing can be implemented. One

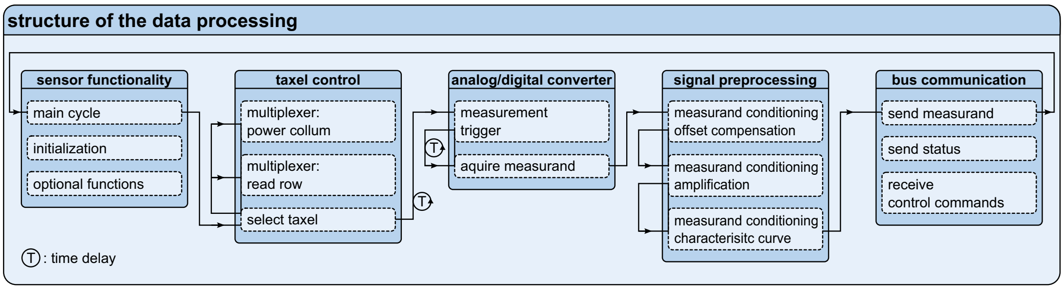


Figure 3.77: Sensor data acquisition and preprocessing structure, according to Schnös [135]

of the bottlenecks for the reduction of the reaction time is the applied bus system for the communication between artificial skin and the control unit of the robotic system. In order to account for a future functional and spatial integration into a robotic system the selection of the applied bus system has to be based on the spatial restrictions arising from the integration. The following parameters determine the choice of bus system for highly integrated mechatronic systems:

- Number of required cables
- Size and number of the electronic components required for the implementation
- Required shielding, e.g. shielding of individual cables
- Data rate
- Overhead per package in percent
- Power consumption
- Robustness of data transmission
- Bus topology

According to Schneider [134] one of the best compromises for the application in a human sized hand is offered by the so called controller area network (CAN) bus system. The application of CAN bus systems in mass products results in small bus controller components that allow for the design of a bus system in the geometrically constraint environment of a human sized robotic hand. In Schneider [134] a new version of the readout electronics is implemented.

Herein the readout strategy proposed in section 3.2.6 is implemented. In order to increase the readout frequency and thus to minimize the reaction time of the artificial skin sensor system in case of a collision the design of the electronics is adapted. Instead of the formerly applied multiplexers a set of analog matrix switches is integrated. Theses switches allow for the combination of numerous taxels and thus enables the formation and dynamic configuration of the size and shape of the virtual receptive fields.

The tactile information is provided through three independent channels, based on three independent layers of communication. The communication between artificial skin readout electronics and the robot control system consists of: Firstly, a bi-directional high level information transmission channel, e.g. for the transmission of the orientation of a detected edge of an object in physical contact with the artificial skin surface. Additional high level information, e.g. the thermal conductivity of an object can be transmitted applying the same communication channel. The second layer consists of a bi-directional mid-level real-time channel for the transmission of the filtered and compressed array data from the artificial skin to the robot control system in order to create a data basis for elaborate shape recognition computations that are too time consuming to be executed directly in the distal artificial skin readout electronics. The information flow from the robotic system towards the artificial skin contains the information which taxel surface normals are oriented in the direction of a planned motion of the robotic system. In the opposite direction the information of the current configuration (location, size, shape, involved taxels) of the dynamic receptive fields is conveyed. In addition the averaged activation level of the individual receptive fields, a detected movement of the center of mass of the contact and information regarding initial slip detection can be provided. The third layer consists of a digital "early-warning", initial-contact signal that is propagated via a separate hardware channel. Practically this can be e.g. a twisted pair cable.

4

Experiments and Results

Review publications, e.g. [20] and [188] reveal the lack of a standardized performance metrics for tactile sensors and the accompanying readout systems. As the authors struggle to compare the published properties of different tactile sensor systems, the lack of a standardized test procedure for tactile sensor systems becomes apparent. Currently, each research group applies a specialized testing procedure for the evaluation of the performance of their tactile sensor system. The test setup proposed by Hristu et al. [56] involves a mechanical 5-DOF apparatus for manual indentation of a compliant robotic fingertip. The proposed test procedure involves the subsequent manual indentation of pre-defined locations on the fingertip. The presented test procedure is very sensor–specific as e.g. no planar tactile sensors could be evaluated with the proposed test scenario. In addition, the high variance of the manual input parameters prevents the reliable comparison of different tactile sensor approaches. The presented approach exemplifies, that there is a need of a standardized testing procedure in order to create comparable results for the evaluation of the performance of the presented tactile sensor systems. Thus, a certain test biasing is immanent if one creates a tactile sensor and then designs a testbed for this sensor. Many of the test facilities presented in literature are based on highly expensive, high precision laboratory equipment that not all research groups are able to acquire. Thus, the repetition of the conducted experiments often is not possible and a direct comparison of the performance of different tactile sensor systems is prevented. Therefore, in the following section a simplified standard test procedure based on the reduction of input variables is proposed to enable a cost effective comparable performance evaluation of different tactile sensor systems.

4.1 A standard test for tactile surface sensors

The focus of the presented standard test procedure is the limitation of variable input parameters and create a set of tests that, while being of simple design, allow for the evaluation of the performance of tactile sensor systems. The proposed metrics for the evaluation of tactile sensors defines criteria for the evaluation of tactile sensors based on a standard set of stimuli that enable comparative testing applying cost efficient testing equipment. While the performance of a tactile sensor without the accompanying readout electronics is interesting from a scientific point of view, the performance of a tactile sensor alone is not meaningful for the application in the target system. In order to account for the multitude of application scenarios for tactile sensor systems in robotic systems the proposed testing procedure consists of the evaluation of static and dynamic transduction properties.

4.1.1 Static indentation testing

For the evaluation of the absolute sensitivity threshold of tactile sensor systems it is necessary to define when a contact event can be classified as detected. Especially, polymer based tactile sensors are subject to noise and drift phenomena. If these effects are deterministic, the readout electronics can be utilized to partially compensate for these undesired effects. If the filtering characteristics of the readout electronics are optimized for the cancelation of noise from the signal, the reaction time of the sensors system will be increased. The goal for tactile sensor systems is to identify the optimal compromise between noise cancelation and reaction time. With respect to the operation of tactile sensors on a robotics system, e.g. to trigger an emergency stop in case of a collision, it is important to reduce the number of false positive detections. In order to do so, the threshold for the detection level has to be increased. Consequently, the initial sensitivity of the tactile sensor system is decreased. Again, the compromise between sensitivity and number of false positive detections will be optimized to the application site and specific task. To enable the comparison of different tactile sensor systems that apply different compensation strategies, it is useful to relate the performance metrics to the characteristics of the output signal of the readout electronics. Only if all characteristics are analyzed for a specific tactile sensor system and electronics configuration a comparison of two different tactile sensor systems is enabled. The following minimum set of characteristics has to be reported:

- Reaction time
- Signal to noise ratio
- Initial sensitivity

Standard indentation spheres Depending on the targeted site on the robotic system different indentation characteristics are required to enable the assessment of the performance of the tactile sensor system. Therefore, a wide range of input stimuli is required. At the same time, the number of variable input parameters has to be reduced in order to enable comparable test results for different tactile sensor systems. Instead of designing a large variety of indentation probes, a set of steel ball bearing spheres of different diameters is chosen as standard indentation probes. These indentation spheres are then applied in a static and dynamic test procedure. Hence the variable input parameters for the static indentation testing are restricted to diameter and density and thus to the weight of the standard indentation sphere. In order to cover the required measuring range from one gram to one kilogram a set of indentation spheres with a diameter ranging from one millimeter to 63 millimeters is chosen. The majority of the tactile sensor prototypes presented in literature consists of taxels that exhibit a location–dependent sensitivity, i.e. depending of where on the surface area of a single taxel an external indentation force is applied, different transduction properties will be observed for a single taxel. Increasing the radius of the indenting object will decrease the location dependency of the transduction properties. For the generation of comparable test results it is therefore important to determine the minimum required radius of the indenting object that results in an equally distributed transduction characteristic of the individual taxels. For the standard test procedure the radius of the applied indentation sphere R_{obj} has to be larger than the distance between the centers of two adjacent taxels $T_{x,y}$:

$$R_{obj} >> T_{x,y} \tag{4.1}$$

5-2-5 static indentation test

For the assessment of the static transduction properties a so called $5-2-5$ static indentation test is proposed. This test targets the evaluation of the static sensitivity and repeatability of the tactile sensor system. The following test procedure is proposed: Record the output from the readout electronics for the unloaded sensor for a five seconds time interval. The average value and the noise of the signal are determined as a reference for the assessment of the detection threshold. Subsequently a test sphere with an appropriate diameter is manually applied on the surface of the sensor. In order to eliminate the influence of the dynamic indentation, a holding time of two seconds is proposed. Following, the output signal from the readout electronics from the indented sensor is recorded for a subsequent time interval of five seconds. The following characteristic values for the sensor can be derived from the $5-2-5$ static indentation test:

- Static initial sensitivity
- Static measuring range
- Repeatability of the transduction properties

The static initial sensitivity (SIS) of the tactile sensor system relative change of the output signal induced by the indentation of a standard indentation sphere related to sphere diameter. A minimum of ten subsequent repetitions of the $5-2-5$ static indentation test creates the data basis for the determination of the SIS value of the tactile sensor system. The SIS consists of the diameter of the applied indentation sphere and the relative change of the output signal with relation to

the signal to noise ratio (SNR). The smallest indentation sphere that results in the defined change of the sensor output signal with respect to the SNR defines the SIS of the tactile sensor system.
The static load limit is defined by the diameter of the indentation sphere that results in the saturation of the loaded taxels. Consequently, the static measuring range is defined by the static initial sensitivity and the static load limit.

Number of activated taxels A second basic criterion for the performance of a tactile sensor system is the number of tactile elements responding if the sensor surface is statically or dynamically loaded with a defined indentation sphere. The number of activated taxels in combination with the prior knowledge of the radius and thus of the curvature of the indenting standard test sphere allows for the comparison of the mechanical compliance of the surface of a tactile sensor system.

Activation radius A third important parameter for the evaluation of the performance of a tactile sensor system is the surface area of a single taxel. Depending on the form of the receptive field of a taxel the surface area of a single taxel can be e.g. circular or quadratic. Assuming a circular shape and a radius equaling half the spatial resolution the surface area can be described as:

$$A_{Tc} = \left(\frac{x_R}{2}\right)^2 \cdot \pi \tag{4.2}$$

Based on the number of activated taxels in one axis on the surface of the tactile sensor the activation radius can be determined. The maximum extension, i.e. the number of activated taxels times the spatial resolution results in the activation radius of the tactile sensor system.
The indentation of a compliant surface with a spherical object results in a ball scraper contact area (A_{bs}). The extension of the contact area can be described as:

$$A_{bs} = 2 \cdot r \cdot z \cdot \pi \tag{4.3}$$

where r is the radius of the indenting sphere and z is the indentation depth. For small indentation depth the surface area of a ball scraper can be approximated with a planar projected circular area on the tactile sensor surface. The activation radius (R_{act}) can be described as a function of the maximum number of activated taxels (n_{tx}) and the spatial resolution of the tactile sensor in this axis (x_{rx}).

$$R_{act} = \frac{(n_{tx} - 1) \cdot x_{rx}}{2} \tag{4.4}$$

Hence, the projected planar contact surface area (A_{proj}) can be described as:

$$A_{proj} = R_{act}^2 \cdot \pi = \left(\frac{(n_{tx} - 1) \cdot x_{rx}}{2}\right)^2 \cdot \pi \tag{4.5}$$

For the determination of the pressure applied to the surface of the tactile sensor the weight of the indentation sphere is determined as a function of the density of the applied steel, the volume defined by the radius of the indentation sphere and the normal gravity at the site of the lab.

$$F_g = \rho \cdot V_{sphere} \cdot g \tag{4.6}$$

Where ρ is the density, V the volume and g the normal gravity. The averaged projected pressure on the activated taxels can be described as:

$$P_{proj} = \frac{F_g}{A_{proj}} \tag{4.7}$$

where

$$P_{proj} = \frac{4 \cdot r^3 \cdot \rho \cdot g}{3 \cdot \left(\frac{(n_{tx}-1) \cdot x_{rx}}{2}\right)^2} \tag{4.8}$$

From the projected pressure (P_{proj}) the averaged force on a single taxel (F_T) can be described as:

$$F_T = P_{proj} \cdot A_{Tc} \tag{4.9}$$

4.1.2 Dynamic indentation testing

For the application in robotic systems tactile sensor systems have to acquire dynamic contact events. Especially the discrimination between intended pHRI and involuntary collisions requires the evaluation of the course of the indentation forces over time. To evaluate the dynamic transduction properties of a tactile sensor system mostly specialized testbeds are designed. One major drawback of the tests conducted on specialized testbeds is the dependency of the results from the actuation of the testbed, e.g. on the chosen actuator, the applied force gauge, as well as the control strategy (e.g. force or position control). Therefore, the following test strategy aims towards a setup that does not require an actuator to create the desired dynamic indentation. Applying the proposed standard indentation spheres as indentation objects, gravity is utilized as a source for the mechanical energy required for the desired dynamic indentation. The basic principle is the mechanical fixation of the indentation sphere at a defined height over the surface of the tactile sensor system. Upon the release of the sphere the light barrier L_0 detects the start of the dynamic indentation test (t_0), see figure 4.1 (a). Following, gravity accelerates the sphere towards the surface of the sensor. A second light barrier L_1, that is located directly over the surface of the tactile sensor detects the begin of the indentation of the tactile sensor (t_1),figure 4.1(b). The elastic properties of the polymer based tactile sensor surface result in an indentation of the sphere while the sphere is

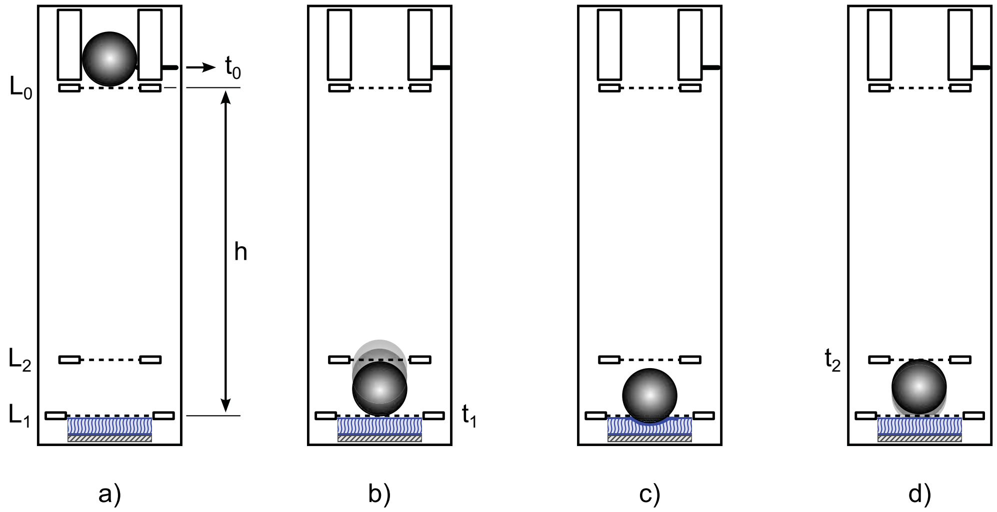


Figure 4.1: Principle of the standard procedure for the dynamic indentation test of the performance of tactile sensors.

decelerated and the kinetic energy is transferred to the tactile sensor. Subsequent to the equilibrium between indentation and restoration force, the sphere is accelerated in the opposite direction by the restoration forces of the deformed polymer material. The duration of the indentation depends on the weight, the velocity at the initial contact and the mechanic damping properties of the applied sensor material. L_1 is activated for the duration of the indentation, see figure 4.1(c). A third light barrier L_2, that is located at a distance over the surface of the tactile sensor that equals the diameter of the indentation sphere, detects the release of the sphere and thus indicates the end of the indentation phase (t_2), see figure 4.1(d).
This dynamic impact test procedure allows for the evaluation of the following properties of the tactile sensor system:

- Dynamic initial sensitivity
- Response time
- Mechanical damping properties
- Restoration time after release
- Overload testing

Following, the characteristic time intervals are outlined.
According to the law of conservation of energy the potential energy is transferred to

kinetic energy:

$$m \cdot g \cdot h = \frac{1}{2} m \cdot v^2 \tag{4.10}$$

The velocity of the indentation sphere at the instant of impact (v_{sphere}) is defined by

$$v_{sphere}(t_1) = \sqrt{2 \cdot g \cdot h} \tag{4.11}$$

According to:

$$v_{sphere}(t_1) = g \cdot (t_1 - t_0) \tag{4.12}$$

and

$$\sqrt{2 \cdot g \cdot h} = g \cdot (t_1 - t_0) \tag{4.13}$$

The height upon release (h_{init}) can be determined from the time interval between the activation of L_0 at $t = t_0$, and the activation of L_1 at (t_1).

$$h_{init}(t_0) = \frac{g(t_1 - t_0)^2}{2} \tag{4.14}$$

Thus, the measurement of the initial distance between the motionless sphere and the surface of the tested tactile sensor can be replaced by the measurement of the time elapsed between the release of the sphere at $t = t_0$ and the activation of the light barrier on the surface of the tactile sensor, at $t = t_1$.

The dynamic initial sensitivity of the tactile sensor system can be determined as a function of the diameter of the applied indentation sphere and the initial height h. The mechanical energy that is required to generate a reliable detection can be estimated from the transferred impulse.

$$E_{min} = \frac{1}{2} m \cdot v(t_1)^2 = \frac{1}{2} m \cdot (g \cdot (t_1 - t_0))^2 \tag{4.15}$$

The minimal release height to generate a measurable sensor output in combination with the diameter of the applied sphere defines the dynamic initial sensitivity of the tactile sensor system. The response time of the tactile sensor system can be determined from the time interval between the activation of L_1 at $t = t_1$ and the time when the initial response signal from the readout electronics reaches the detection threshold defined in section 4.1.1.

The mechanical compliance of the sensor surface can be estimated from the time interval between the initial contact (t_1) and the release of the indentation sphere from the surface after the indentation (t_2) in relation to the initial height h.

The duration of the second activation of L_2 can be applied as an estimate for the velocity of the backscattered indentation sphere. Especially, for the application of artificial skin as a mechanical damping layer for the cushioning of a collision of the robotic system with its environment it is desired to dissipate as much kinetic energy in the mechanical damping layer of the skin as possible. A minimum velocity of the backscattered sphere indicates a high fraction of kinetic energy dissipation. The acceleration of the backscattered sphere ceases at the lift-off of the sphere from the surface of the tactile sensor and can be detected by the second activation of L_2 at (t_2). The dissipated energy ($E_{dissipated}$) can be estimated from the difference in velocity before and after the indentation period.

$$E_{dissipated} = E_{kin}(t_1) - E_{kin}(t_2) \tag{4.16}$$

$$E_{dissipated} = E_{kin}(t_1) - E_{kin}(t_2) = \frac{1}{2}m \cdot (v(t_1) - v(t_2))^2 \tag{4.17}$$

$$E_{dissipated} = \frac{1}{2}m \cdot (g \cdot (t_1 - t_0) - (2R_{sphere} \cdot (t_2(off) - t_2(on))))^2 \tag{4.18}$$

For the assessment of the restoration time after the release of the sphere from the surface the time interval between the second activation of L_2 and the convergence of the output signal from the readout electronics to the value prior to the indentation is acquired. Where appropriate, the convergence to 95% of the initial value is sufficient. Figure 4.2 depicts a sequential series of high speed images taken at $600fps$. The top of the figure depicts a sequence on every fifth frame acquired. In order to illustrate the ability of the presented tactile surface sensor system to record the course of the indentation resulting from the impact, the bottom of the figure depicts a series of high speed images acquired at $600fps$ where every subsequent frame is depicted.

Overload testing

In the following, a test procedure for the evaluation of the robustness of the tactile sensor surfaces the ability to withstand collision consequences like high local pressure induced by a collision between a fast moving robot and a rigid obstacle is proposed. Collision forces between robots and humans have been analyzed by Haddadin et al. [47]. The authors state, that the maximum impact forces during a collision between a DLR LWR III and a specialized head-dummy were measured as high as $2.5kN$ for velocities of $2m/s$. In order to enable a test setup, that allows for the assessment if a tactile sensor system is capable to withstand such impact forces a suitable testbed is required. At DLR a impact test facility for the evaluation of impact tests is available, the setup is described in Haddadin et al. [48]. An impactor is positioned in a defined hight over the test specimen. The impactor is released and collides with the specimen. The impact forces are acquired by a high speed force sensor located within the impactor. In order to to evaluate if the tactile sensor prototypes are capable to withstand high indentation forces apparent during a collision the prototypes are tested on the impact test setup described in

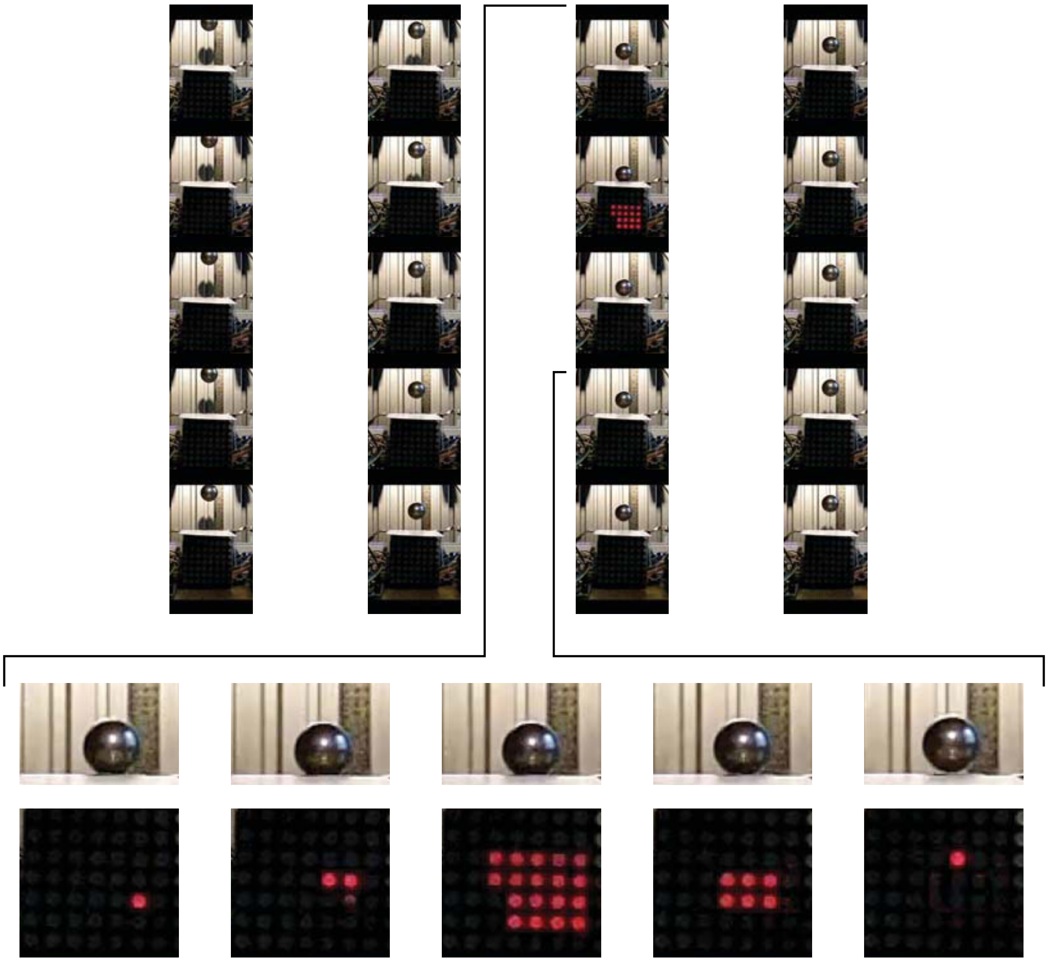


Figure 4.2: Dynamic indentation test of the performance of tactile surface sensor based on the described standard test. The high speed photographs are recorded with $600 fps$. On top, a sequence of every fifth frame of the high speed images is depicted. On the bottom every frame is depicted to illustrate the ability of the tactile surface sensor system to record the course of the impact of the sphere.

Haddadin et al. [48]. The weight of the impactor is defined as $2158g$ with a radius of the impact surface of $20mm$. In order to evaluate the layer setup of an artificial skin proposed in section 3.2.7 the prototype of the tactile surface sensor is located on top of a layer of the damping material evaluated in section 3.3.2. The test setup is adapted from the test facility proposed in DIN EN 1621-1 [24] for the assessment of protective clothing for motor-cyclists. The test setup is altered with respect to the design of the impactor. Instead of a square plate a hemispherical impactor with a radius of $20mm$ is applied. Thus, a point contact between impactor and anvil is created. Thus, the damping and load distribution characteristics of the evaluated damping material are evaluated for a simulated impact between a rigid object and a robotic system covered with an artificial skin. Figure 4.3 depicts a series of sequential high speed images acquired at $600fps$. The sequence illustrates the ability of the tactile surface sensor to elastically deform its shape and thus conform to the deformation of the underlying mechanical damping material. A measure for the collision tolerance of the respective tactile sensor is the release hight and thus the impact force the sensor can withstand damaging of the taxels at the location of the impact. The functioning of the sensor can be assessed by a follow up $5-2-5$ static indentation test with the smallest detectable indentation sphere prior to the overload test. In order to exemplify the dynamic transduction capabilities of the tactile surface sensor prototype implemented within this thesis, the sensor output during

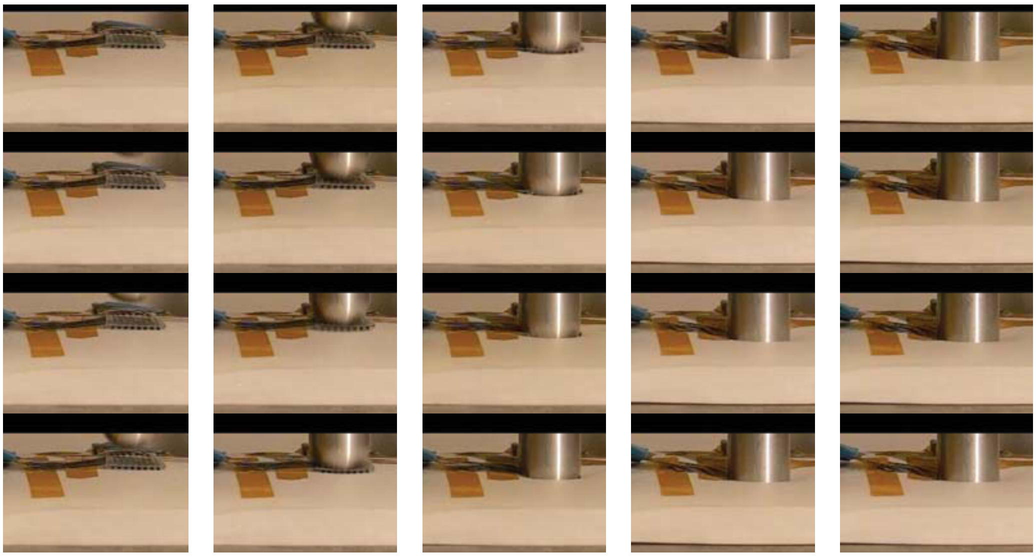


Figure 4.3: Dynamic overload test with $1.5m/s$, the radius of the hemispherical indentation object is $20mm$. The weight of the indentation object is $2158g$. The images are acquired at $600fps$, subsequent frames are depicted in the above figure.

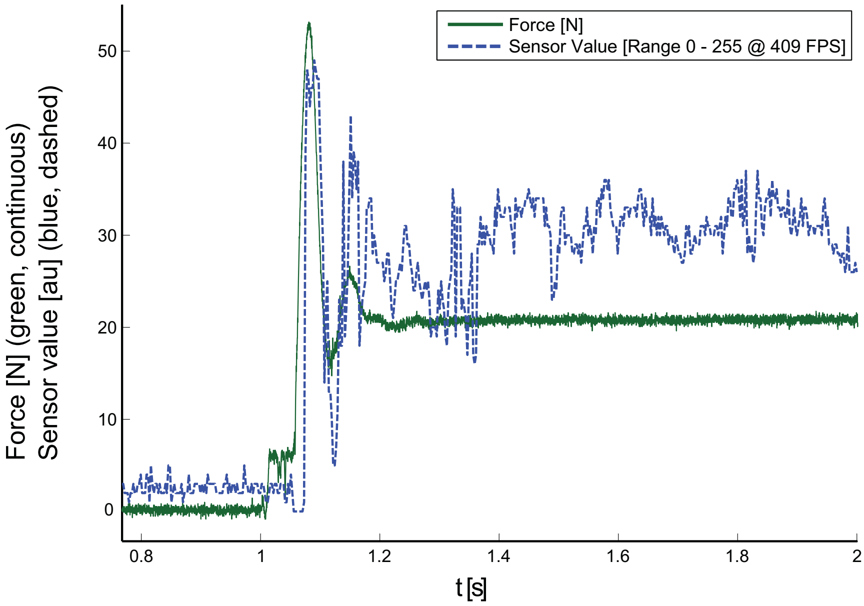


Figure 4.4: Dynamic response of the tactile surface sensor prototype during the overload testing. The depicted graph illustrates the capability of the presented prototype to withstand the high impact forces and at the same time acquire tactile data at a rate of $409fps$; Figure curtesy of Schneider [134].

the impact of an overload test with an indentation velocity of $0.5m/s$ is depicted in figure 4.4. The depicted graph illustrates that the presented prototype of the tactile surface sensor is capable to withstand high indentation forces resulting from an unintended collision and at the same time is capable to acquire tactile data from the individual taxels at a rate of $409fps$.

4.2 Application

While the environment of the laboratory provides controllable conditions for the evaluation of the sensory capabilities of the surface sensor, it lacks real world interferences like electromagnetic fields, changes in ambient temperature, humidity, dirt and most challenging - the human user. Influences tactile surface sensors have to deal with in out-of-the-lab, real world, application. Therefore, the tactile surface sensor is integrated into different robotic applications to test its fitness for applications in human everyday environment. At the same time these experiments demonstrate that the surface sensors are truly implementable. For the assessment of the contribution of the proposed artificial skin setup to the overall safety of the robotic system a prototype of the artificial skin is applied on the covering structure of a DLR LWR III. The data acquired trough the tactile surface sensor is applied to compute a signal to trigger the emergency stop of the robotic system. The experiments are conducted at the velocity of $0.2\ m/s$ of the tool center point of the robotic system. As the damping material cushions the impact, the initially transmitted impact force can be reduced. In addition, the torque applied by the motors of the robotic system can be reversed, the brakes activated and thus the entire robotic manipulator can be decelerated. Figure 4.5 depicts three sets of sequential photographs of the experiments conducted with the artificial skin on a DLR LWR III. The first series depicts the detection of the collision between the artificial skin and a toy flower with small interia. Even the contact of the freely moving bloom suffices to trigger the emergency stop of the robotic system. The second series depicts the successful detection of the contact of a single post-it® sheet. The contact is detected and the emergency stop of the robotic system is triggered. The third series exemplifies the ability of the presented artificial skin to detect a collision between the artificial skin and soft tissue (the authors nose). The artificial skin reliably detects the contact and triggers the emergency stop of the robotic system.

4.3 Results

Based on the proposed general design concept a set of tactile surface sensors for the application on robotic systems have been implemented within this thesis. The spatial resolution of the presented prototypes ranges from $1.25\ mm$ to $20\ mm$. For the future integration into robotic fingertips a first prototype with a spatial resolution of $1.25\ mm$ has been implemented. The elastic stretchability of the prototype is prerequisite for the artificial skin to conform to the highly curved surface of modern robotic fingertips. To evaluate the proposed manufacturing processes a series of prototypes exhibiting a spatial resolution of $2.5\ mm$ has been manufactured. The implemented tactile surface sensors exhibit different transduction properties that are required for application on the different application site on a robotic system. In order to evaluate the adaptability of the proposed manufacturing processes for the implementation of large area tactile surface sensors a prototype with a spatial resolution of $20mm$ has been implemented. Thus, the implemented prototypes demonstrate the scalability of the spatial resolution as well as the scalability of the surface area of the artificial skin. In addition, the proposed direct extrusion printing process enables the implementation of a scalable artificial skin that can be adapted to the respective application site on the robotic system. The manufactured prototypes demonstrate the feasibility of the adaptation to the requirements of the application site on the robotic system. Thus it could be shown, that the proposed overall concept for an artificial skin is suitable for the future implementation of a

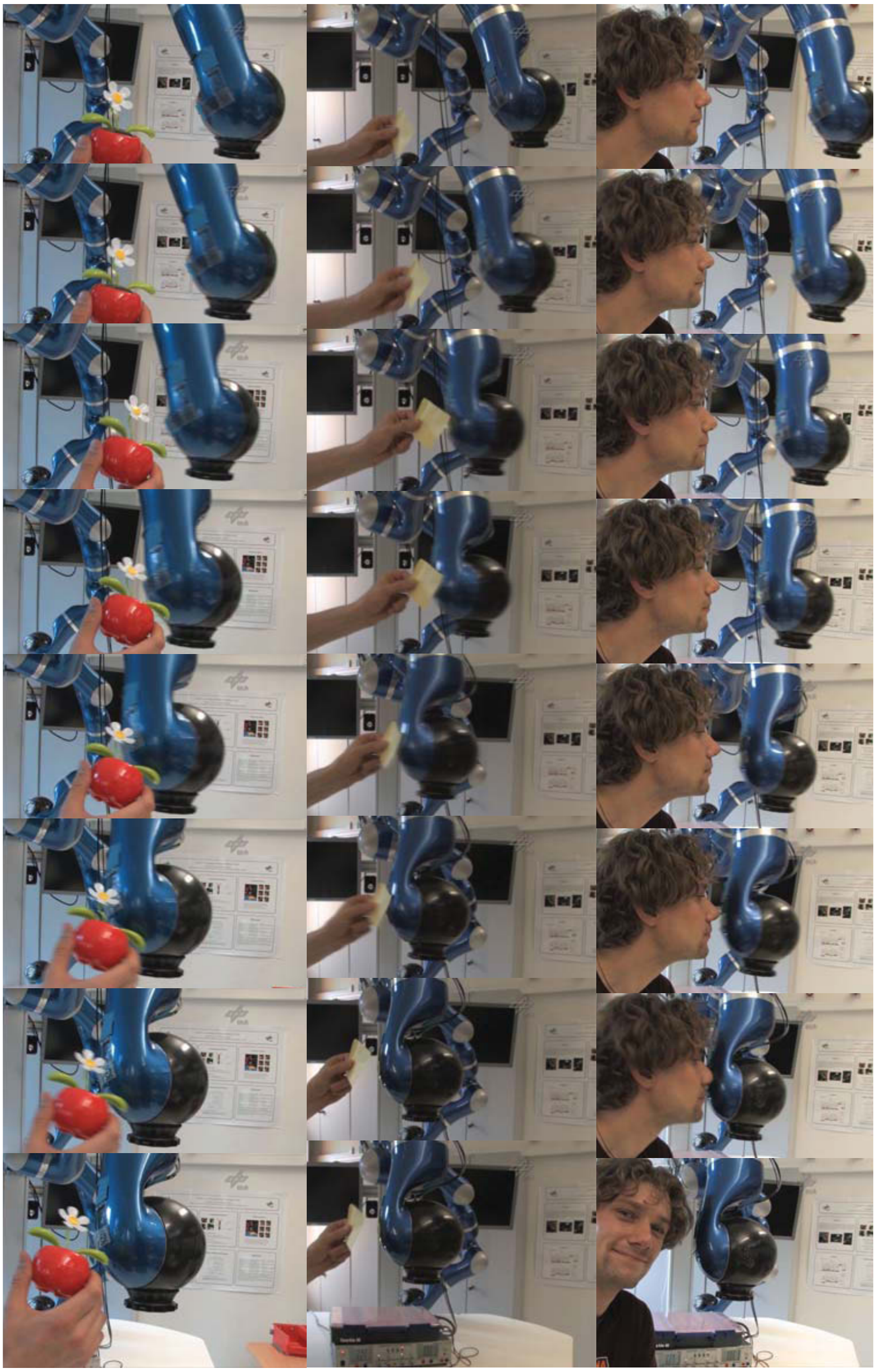


Figure 4.5: First experiments for the artificial skin based collision detection. Collision detection with a toy flower with small inertia (left), collision detection with a single post-it$^{\circledR}$ sheet (middle), facial collision with the author's nose (right)

whole-body touch sensitive cover for entire robotic systems.

The static initial sensitivity of the presented prototypes is sufficient to detect an external indentation force of $0.05\ N$ that is exerted onto the surface of a single taxel. The conducted static indentation tests revealed, that the static transduction properties of the proposed sensor setup can be further optimized with respect to the achieved static measuring range of the individual taxels. The conducted dynamic indentation tests and the application of the prototypes on the DLR LWR III show, that the proposed data acquisition and transmission concept for the sequential increase of information depth enables the increase of the framerate from $400fps$, if every taxel is acquired sequentially, to $1000fps$, if all taxels of a sensor patch are combined. The combination of the individual taxels results in the formation of a virtual receptive field that can be read out without the restrictions that arise e.g. from the switching in a multiplexer. Thus, the time artificial skin requires to detect a contact event can be decreased from $2.5ms$ to $1.0ms$.

The overload testing of the manufactured prototypes demonstrates the effectiveness of the combination of dedicated functional layers to form a multifunctional artificial skin. The elastic deformability of the implemented tactile surface sensors enables the superficial sensors to conform to the deformation of the underlying mechanical damping layer in case of a collision. Thus, the proposed setup enables the tactile surface sensor to withstand a collision without mechanical damage. In addition, the investigated passive mechanical damping layer below the tactile surface sensor is capable to cushion the impact and thus passively reduce the collision severeness. The time interval between the detection of a collision by the tactile surface sensors and the active reaction strategies to take effect can be bridged by the deformation of mechanical damping layer. First experiments with respect to physical human robot interaction based on information derived from the artificial skin sensor prototype exemplify that an intuitive interaction between human user and robotic system can be implemented based on artificial skin data.

5

Conclusion and Outlook

The desired direct physical interaction between human user and robotic system in a joint workspace requires new safety and interaction concepts. In order to allow for a safe and intuitive interaction between human user and robotic system the surveillance of the surface structure of the robotic system with respect to physical contact is required. The availability of an artificial skin equivalent for robotic systems has been foreseen for a long time but the plentitude of information that can be derived from physical contact by human skin is still unavailable for technical systems. The spatial and functional integration of tactile sensors into a robotic system is one of the key challenges to be solved. The derivation of an artificial skin that allows for the successful integration into a robotic system requires an operation–oriented design approach that takes into account the constraints arising from the overall system. Especially, the covering of the 3D-curved surfaces of modern robotic systems restricts the application of available tactile sensor systems. Therefore, within this thesis an overall concept for an implementable artificial skin for robotic systems has been derived.

5.1 Conclusion

The proposed overall concept for the design of a multifunctional artificial skin anticipates the constraints of a future spatial and functional integration into a robotic system and accounts for the requirements of an operation on a robotic system in real world applications. Based on a set of design paradigms the overall concept supports the solution of goal conflicts during the development of the artificial skin. The applied partitioning of the functional range of the artificial skin allows for the dedicated design of specialized materials for the individual functional components. Thus, the pursued approach avoids tradeoffs, e.g. between the desired sensitivity and the required collision tolerance. The integrative development of the functional components and the underlying scalable manufacturing processes allows for the implementation of an artificial skin that can be scaled with respect to surface area, spatial resolution and sensitivity.

The feasibility of the desired scalability of the spatial resolution could be shown in various prototypes that exhibit spatial resolutions ranging from 1.25 millimeter to 20 millimeters. The implemented prototypes thus demonstrate, that the pursed approach enables tactile surface sensors that can be adapted to the requirements of the respective application site on the robotic system. In addition, the manufactured tactile surface sensor prototypes can be applied on the 3D-curved surfaces of modern robotic systems and thus demonstrate, that the proposed overall concept solves one of the major challenges on the way towards a touch sensitive whole-body cover for entire robotic systems.

The successful development of specialized materials, enabling the implementation of the individual functional components, provides a toolbox of functionalities that can be combined in order to adapt the properties of the artificial skin to the requirements of the application site on the robotic system.

The derived design paradigms allow for the development of tactile surface sensors, that solve the goal conflict between sensitivity and a collision tolerant - overload proof design. The solution of the most prominent goal conflict is exemplified by the implemented prototypes, that are capable to detect an external indentation force as low as $0.05N$ while at same time are robust enough to withstand collision forces exceeding $50N$. The proposed strategy for the sequential increase of the information depth enables a tactile sensor system that is able to detect a collision in 1.0 millisecond.

For the assessment of the implemented artificial skin system the performance is compared to the set of overall requirements for ideal tactile sensor systems, introduced by Harmon [50]. The presented artificial skin system is capable to fulfil the following requirements:

- Compliant and durable surface ✓
- $1mm$ to $2mm$ spatial resolution ✓
- $1g$ to $10g$ minimum sensitivity ✓
- $1000:1$ dynamic range ☐ (future challenge)
- Monotonic output ✓
- At least $100Hz$ frequency response ✓
- High stability and repeatability ☐ (future challenge)
- Low hysteresis ✓

The implemented prototypes do not only fulfil the majority of the requirements for an ideal tactile sensor, but are in addition based on scalable manufacturing processes that allow for a cost effective manufacturing of large area artificial skin. The presented artificial skin is capable to cover the 3D-curved surfaces of modern robotic systems. The ability of the artificial skin to conform to the shape of the robotic system may help to increase the acceptance of the human user.

Moreover, the elastic stretchability of the implemented tactile surface sensors enables the introduction of a passive mechanical damping layer into the overall artificial skin and thus contributes to an increase of safety during direct pHRI. Furthermore, the combination of the information from the intrinsic joint torque sensors with the tactile data derived from the tactile surface sensors forms the basis the implementation of a redundant safety system for pHRI.

Moreover, the scalability of the spatial resolution allows for the design of touch sensitive covers for robotic fingertips and prosthesis. The proposed combination of highly sensitive, stretchable tactile surface sensors with an underlying mechanical deformation layer may contribute to the enhancement of the fine dexterity of robotic hands and prosthesis.

Thus the presented thesis contributes to the long term evolution of tactile sensors towards a future multifunctional artificial skin that can be applied as a touch sensitive whole-body cover for entire robotic systems. The integration of an artificial skin will help to increase safety and enable an intuitive physical interaction between humans and robotic systems. Thus, the presented thesis may contribute to the future successful integration of robotic systems in human everyday environment.

5.2 Outlook

With respect to the artificial skin hardware the following properties will be further optimized:
The dynamic range of the individual taxels has to be increased in order to account for the $1000:1$ dynamic range requested by Harmon [50]. Moreover, the ability of the presented tactile surface sensors to withstand high indentation forces has to be extended with the ability to withstand abrasion in long term application. In addition, the stability and repeatability with respect to static or quasi-static indentation forces requires improvement. Further, the concepts for the specialized taxels for the acquisition of shear forces and vibrations will be implemented.
During this thesis a series of new concepts for the further optimization of the proposed artificial skin have been derived. Therefore, future research efforts will, amongst others, address the following ideas:

Intra-sensor scalability of the spatial resolution In order to further tune the transduction properties of the artificial skin to the requirements of the application site an intra-sensor scalability of the spatial resolution is proposed. The concept depicted in figure 5.1 requires a flexible manufacturing process that allows for an adapted positioning and spatial distribution of the individual taxels.

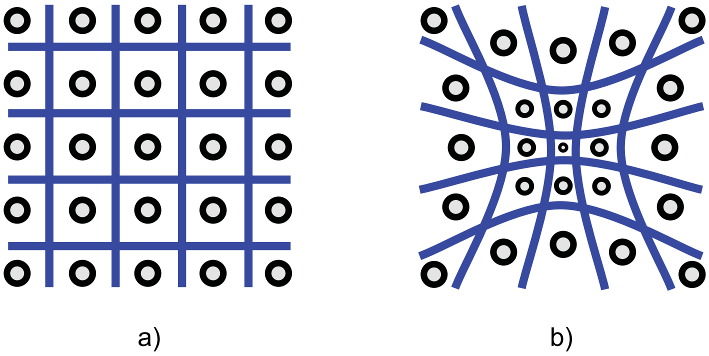


Figure 5.1: The proposed direct extrusion-printing process in principal enables the adaptation of the spatial resolution from an equidistant configuration (a), to a location dependent scaling of the tuning of the spatial resolution within a single sensor patch (b).

Motion dependent tactile attention Based on the knowledge of the motion of a robotic system in its environment, the probability of an intended physical contact or an undesired collision can be determined. If e.g. a robot arm moves in clockwise rotation around its vertical base axis a collision on the counterclockwise surfaces of the robot structure is less likely than a collision on the surfaces facing clockwise. Depending on the angle between the surface normal of the tactile elements with a surface normal and the space-resolved vector of the motion direction a probability map of the robot surface can be defined. A strategy for the adaptation of the readout frequency of the tactile elements on the surfaces averted from the motion direction can be defined. Based on the knowledge of the local curvature of the robot structure, a ration between expected occurrence of a contact in a direction normal to the surface of the tactile sensing element and in tangential direction respectively can be defined. Depending on this ratio the tactile attention can be focussed to the corresponding specialized tactile elements on the surface of the robot structure. Thus, a space- and direction-resolved probability for collisions and contacts can be derived. In combination with a controllable readout strategy for the tactile surface sensor system this collision/contact probability map can be applied for the optimization of the data generation of the surface sensor system and thus help to reduce the computational load without compromising the required high speed readout of the tactile surface sensors.

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A

Appendix

A.1 Volume flow of Newtonian fluids in a cylindrical tube

Following the derivation of the volume flow of Newtonian fluids in a cylindrical tube is presented according to Kuhlmann [74] P.212 - P.214:

> "Parallel shear flow can be described as:
>
> $$\mathbf{u} = w(x,y)\mathbf{e}_z \tag{A.1}$$
>
> where the non-linearity of the Navier-Stokes equations is zero:
>
> $$\mathbf{u} \cdot \nabla \mathbf{u} = 0 \tag{A.2}$$
>
> For parallel shear flow the velocity field is:
>
> $$\mathbf{u} \cdot \nabla \mathbf{u} = (\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z}) w(x,y)\mathbf{e}_z = 0 \tag{A.3}$$
>
> where $u = 0, v = 0$ and δ / $\delta z \rightarrow 0$. If cylinder-coordinates are applied, the symmetry of the cylindrical tube results in:
>
> $$\mathbf{u} = w(r)\mathbf{e}_z \tag{A.4}$$
>
> $$\mathbf{u} \cdot \nabla \mathbf{u} = (u\mathbf{e}_r + v\mathbf{e}_\varphi + w\mathbf{e}_z) \cdot (\mathbf{e}_r \frac{\delta}{\delta r} + \frac{\mathbf{e}_\varphi}{r}\frac{\delta}{\delta \varphi} + \mathbf{e}_z \frac{\delta}{\delta z})\mathbf{u} = 0 \tag{A.5}$$
>
> with equation A.4,
>
> $$w \frac{\delta}{\delta z} w(r)\mathbf{e}_z = 0 \tag{A.6}$$
>
> For the stationary laminar flow in the cylindrical tube $u = v \equiv 0$ and
>
> $$\frac{\delta p}{\delta r} = \frac{\delta p}{\delta \varphi} = 0 \tag{A.7}$$
>
> accordingly the pressure depends of the position on the axis of the tube, $p = p(z)$. Hence the Navier-Stokes equation in cylinder coordinates can be reduced to:
>
> $$0 = -\frac{\delta p(z)}{\delta z} + \frac{\mu}{r}\frac{\delta}{\delta r} r \frac{\delta}{\delta r} w(r) \tag{A.8}$$
>
> As the derivation of the pressure solely depends on z, and the derivation of the velocity field solely depends on r, the equation can only be true for all r and z if the terms are constant:
>
> $$\frac{\delta p(z)}{\delta z} = \frac{\mu}{r}\frac{\delta}{\delta r} r \frac{\delta}{\delta r} w(r) = -K = const. \tag{A.9}$$

Therefore, the pressure $p = -Kz$ linearly decreases in flow direction. The integration of the remaining differential equation for w results in:

$$r\frac{dw}{dr} = -\frac{K}{2\mu}r^2 + A \tag{A.10}$$

With the separation of the variables,

$$dw = (-\frac{K}{2\mu}r + \frac{A}{r})dr \tag{A.11}$$

and an additional integration

$$w(r) = -\frac{K}{4\mu}r^2 + A\ ln(r) + B \tag{A.12}$$

The integration constants are defined by the flow characteristics in a tube, where the fluid adheres to the wall $(w(a) = 0)$, where a is the inner radius of the tube and $w(0) < \infty \rightarrow (A = 0)$. The resulting velocity distribution is called Hagen-Poiseuille-flow:

$$w(r) = \frac{Ka^2}{4\mu}(1 - \frac{r^2}{a^2}) \tag{A.13}$$

where the maximum velocity can be observed for $r = 0$:

$$w_{max} = \frac{Ka^2}{4\mu} \tag{A.14}$$

The volume flow for the cylindrical cross section of the tube $A = \pi a^2$ can be calculated as:

$$\dot{V} = \int_A \mathbf{u} \cdot d\mathbf{A} = \int_0^{2\pi} \int_0^a w(r) r dr d\varphi = 2\pi w_{max}\frac{a^2}{4} = \pi a^2 \frac{w_{max}}{2} \tag{A.15}$$

With $w_{max} = Ka^2/4\mu$ and $K = \Delta p/L$ the volume flow results:

$$\dot{V} = \frac{\pi a^4}{8\mu}\frac{\Delta p}{L} \tag{A.16}$$

The volume flow through a cylindrical tube thus depends on the dynamic viscosity and is proportional to the pressure gradient."

A.2 Model of the contact surface area

In Schnös [135] a model for the description of the relation between the normal deviation of the PBCT and resulting alternation of the contact surface area between the intersecting PBCT. The results of Schnös [135] with respect to the description of the change in contact surface area are summarized in figure A.1.

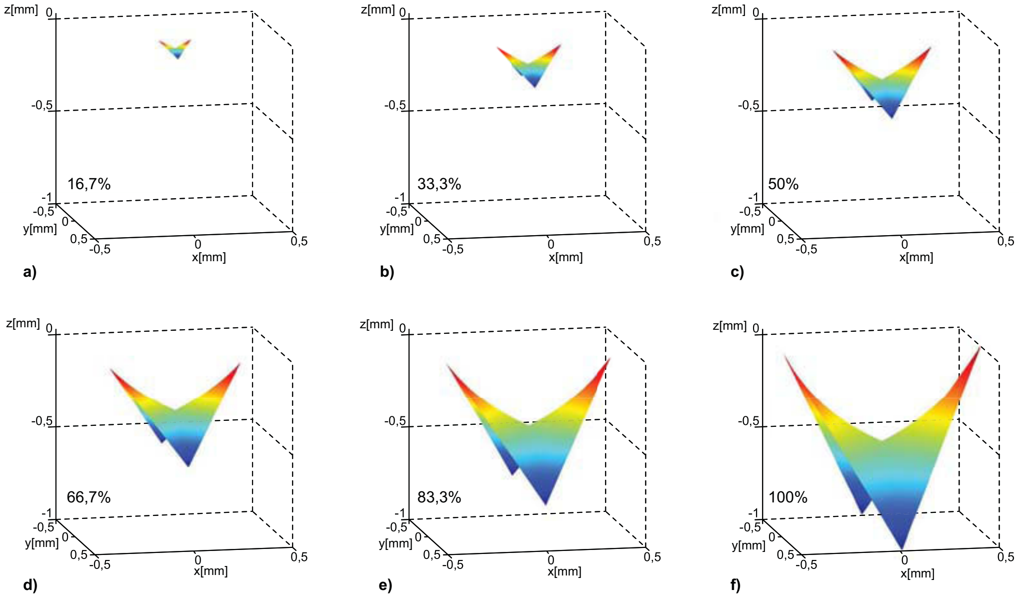


Figure A.1: External indentation force results in a deflection of the upper PBCT and thus results in a change of the contact surface between the triangular PBCT; figure curtesy of Schnoes [135]

A.3 FEM simulation

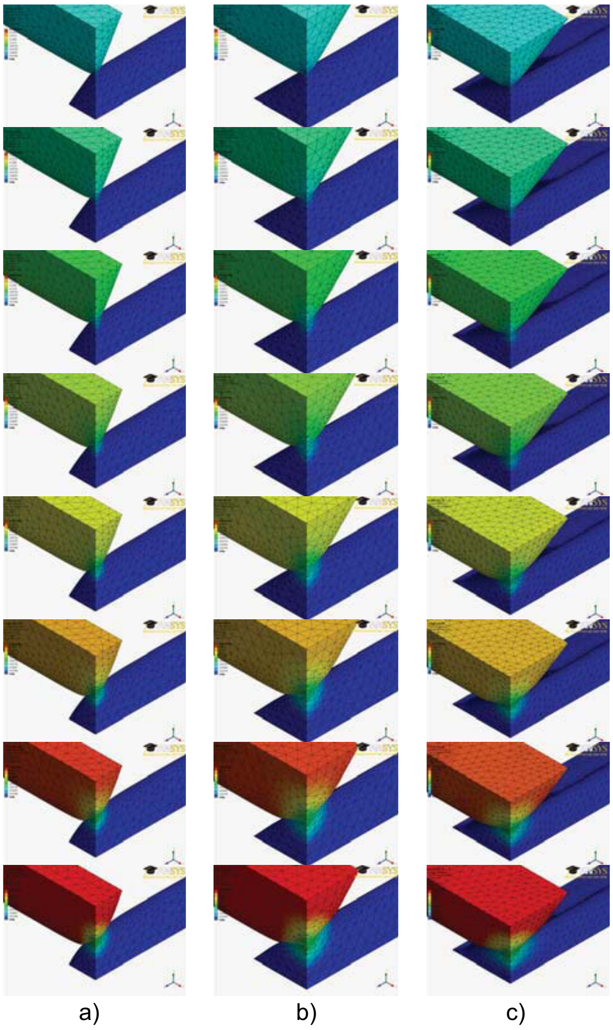
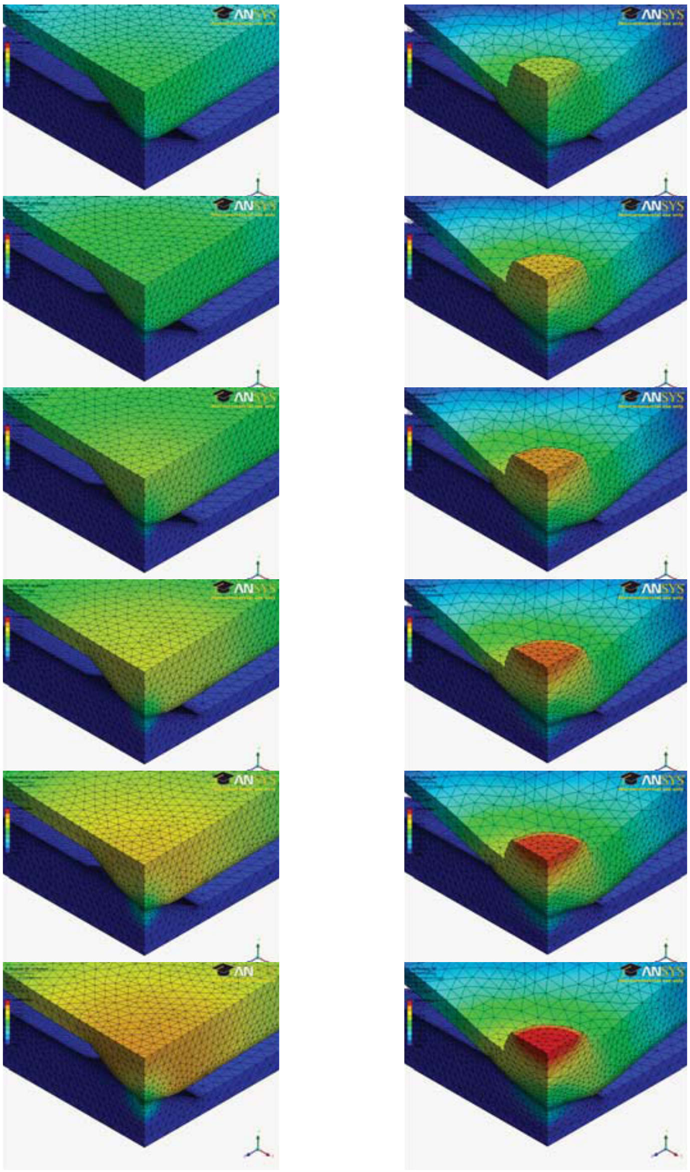

a) b) c)

Figure A.2: External indentation force results in the deformation of the intersecting PBCT and thus evokes a change of the contact surface between the triangular PBCT; Depicted is the overall deformation resulting from the normal displacement of the PBCT with 30 (a), 45 (b) and 60. Figure adapted from Krauss [73]



a) b)

Figure A.3: The simulation of the behavior of the combined functional components shows, that the introduction of the macroscopic surface structure greatly affects the transduction properties of the tactile surface sensor, figure adapted from Krauss [73]

A.4 Photograph of the tactile surface sensor prototype

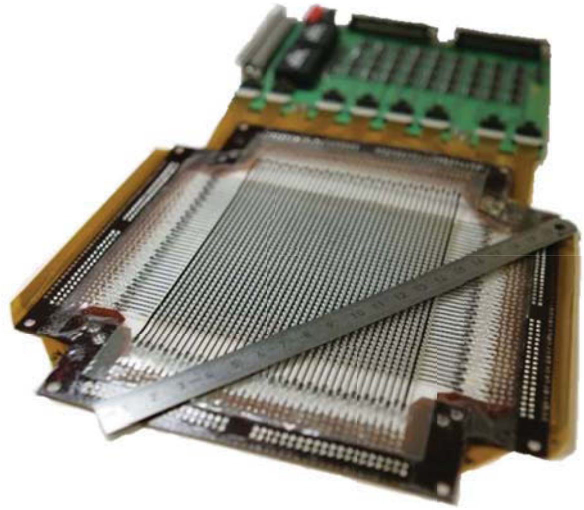


Figure A.4: Prototype of a normal force acquisition tactile surface sensor with 40×40 taxels. The spatial resolution is $2.5mm$