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PrintAssist—a conversational human-machine interface for 3D printers

Abstract: 3D printers are no longer found only in industry, universities or makerspaces but now are increasingly used in domestic settings. Personal fabrication will increase in the coming years, and 3D printing will play an important role in this process. Due to technology and price development, 3D printers are becoming established among casual users at home. However, there are still many hurdles in the use of 3D printers that interfere with their appropriation in everyday life. In this paper, we investigate how chatbots can overcome these hurdles and support onboarding to 3D printing. Furthermore, we explore how chatbots can be used as a human–machine interface and facilitate interaction with 3D printers for both novice and expert users. In a research-through-design approach, we have created a fully functional chatbot that introduces users to 3D printing and helps them perform typical tasks when operating 3D printers.

Keywords: 3D printing; chatbot; conversational interface; human–machine interface; onboarding.

1 Introduction

3D printing is often discussed as one of the major technologies driving the next industrial revolution because its manufacturing characteristics make it ideal for rapid prototyping and individualized products. For a long time, 3D printing could only be found in industry settings due to the high cost and training required to operate such machines. Today, the prices of 3D printers have decreased, and 3D printers are emerging into other application fields such as medicine [1], dentistry [2], arts and crafts [3], fashion [4] and domestic settings [5–7].

However, the skills required to operate a 3D printer remain high even if modern desktop 3D printers provide sophisticated features to prevent breakdowns during the print. Furthermore, 3D printing also includes activities that are not directly related to operating the 3D printer hardware, such as 3D modeling, preparing a virtual model for printing (slicing), and postprocessing. The 3D printing workflow is characterized by a variety of different software tools. As Ludwig et al. [8] show, this variety of different tools coupled with the socio-material dimensions often result in media discontinuities and infrastructure breakdowns and eventually in print errors. This can overwhelm novice users and makes it hard to find the right entry point for 3D printing newcomers. In addition, the traditional human–machine interface (HMI) of a 3D printer with buttons and a small display only serves to operate the machine. The machine fails to provide information on the preparatory activities that must be completed before a print can be started. Beginners need to search for this information from third parties like the manual, the internet or experienced users.

Laplume et al. argue that 3D printing could be the final part of the supply chain [9] at the user's home. They assume that the emergence of 3D printing will continue in domestic settings, wherefore many more novice end users will come into contact with 3D printers. This calls for appropriate tools and methods to handle the current challenges associated with the entire 3D printing workflow from an end-user perspective. Previous studies tackled this challenge, for example, by using different types of augmented reality (AR) like projection-based AR [10] or with AR glasses [11]. However, these approaches are often not suitable for home users. Another possible approach could be using the conversational agents (CA) that have become increasingly popular in recent years. Common use cases for CAs like Alexa or Siri are information retrieval or turning lights on/off. In the latter case, the agent acts as the HMI for the light bulb, replacing the light switch. Most current CA interactions remain on a rather low complexity level [12].

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In a research-through-design approach [13], we want to explore the capabilities of Cas in a more complex context, such as explaining and operating a 3D printer. Therefore, we created a concept of a CA that aims to provide an all-in-one interface for 3D printers that hides the underlying complex components to simplify the workflow. While implementing the concept, we focused on onboarding newcomers to 3D printing and the operation of 3D printers with the necessary preparatory steps, such as downloading a model or preparing the model for printing. The evaluation of our working prototype, called PrintAssist, with a total of 18 participants showed that a chatbot is a suitable alternative to onboard novices to 3D printing. Based on our results, we derive some design implications for chatbot-based HMIs and present lessons learned from the development of PrintAssist.

2 Related work

2.1 Onboarding as the first step of appropriation

Appropriation addresses the circumstances where users attach situated meanings and new usages to certain artifacts. Furthermore, appropriation "refers to the ways in which people adopt and adapt interactive technologies, fitting them into working practices and evolving those practices around them" [14]. Dourish noted that people need to understand to some extent how a new artifact works to understand how to make it work in their practice [14]. The exploration of new artifacts can therefore be seen as an important step of appropriation that we want to support with our conversational HMI.

One important aspect of appropriation is a proper onboarding procedure. The term onboarding is often used in the human resources area and is associated with the process of making new employees an effective part of the company or organization [15]. However, the term is also becoming more common in other areas like software design. Within game design research [16] as well as in product design [17], it refers to the first few minutes of a user's experience in a game or application. Explicit onboarding procedures, especially in software tools or games, support users in understanding the capabilities and functionalities of the artifact. "Onboarding is the process by which you can help users overcome the cold-start problem—a blank profile, an unfamiliar interface, a general feeling of 'what the heck do I do next?'" [15]. Renz et al. [18] define the goal of onboarding as making new users familiar with the product so they can use it efficiently.

As the initial onboarding phase exists with every artifact (analog, digital, physical, virtual) and often poses major hurdles for inexperienced users, it would be useful to design specifically for this onboarding phase and to pay particular attention to the first few minutes of the user experience. Balestrini et al. [19] studied onboarding procedures to IoT. They noticed that the existing setup process took too long, provided little feedback on its progress, and the language used was too technical. These are similar to the experience of onboarding to 3D printing, especially the technical language, which we want to tackle in our study.

2.2 3D printing: practice and appropriation

Both researchers in human-computer interaction (HCI) and private consumers have a rapidly increasing interest in 3D printing [20]. Gershenfeld identifies parallels between the transition from mainframes to personal computers and mass production to personal fabrication and adds that this transition will have greater implications because this time, the physical world will be personalized [5]. 3D printing will play a major role in the rise of personal fabrication [6, 21] because its fabrication method makes it ideal for creating individualized products at home. Furthermore, 3D printers are becoming more sophisticated and at the same time cheaper. However, the shift from the industry into domestic settings will introduce new challenges as more untrained people come into contact with 3D printers. The current design of the devices and corresponding workflow still include obstacles for newcomers that prevent the appropriation of 3D printing by the masses [22–26].

In addition to technical challenges [26], operating 3D printers is challenging for newcomers because the 3D printing workflow includes activities that are not directly related to the machine. To start a 3D print, the user first needs a 3D model that then must be prepared (sliced) for the printer. Next, the file with the sliced model must be transferred to the printer, and the printer must be prepared (e.g., cleaning the build plate or checking the printing material). Usually, the printed object is ready to use after the print. However, there are cases in which the object must be postprocessed (e.g., removing support structures); the user may want to improve the object by sanding or painting it [20]. Each step in this workflow includes several challenges on the machine hardware level (e.g., configuration of the printer), the socio-material level (e.g., the impact of environmental factors such as temperature), and the task/process level (e.g., handling of the needed software). The empirical findings of Landwehr Sydow et al. [24] and Ludwig et al. [25] suggest that a 3D printer is often seen as a "black box" for users, causing confusion and hindering the appropriation of 3D

printers. In addition, due to non-intuitive operational issues, troubleshooting requires an advanced understanding of the machine and print processes [23].

Among the few studies on appropriation support for 3D printers, Ludwig et al. [25] investigated the potential for appropriation support by incorporating multiple sensors into 3D printers. Data from the environment and the inside of the printer are collected and presented to users, allowing them to receive timely feedback on their print jobs and making sense of possible reasons for print failures. In addition, as appropriation is a social phenomenon, they implemented the option to directly share the actual usage data about a printing process with the community. These features are the foundation of the "sociable technologies" concept that aims to support appropriation by providing secondary functionalities such as visualizing data, documenting prints and sharing print settings that are closely integrated into the machine [8]. Later, Jasche and Ludwig [11] moved such appropriation support to a mixed reality application that allows users to learn about and operate 3D printers through augmented reality glasses and to gain insights into the characteristics of the actual 3D model within the real environment.

2.3 Conversational user interfaces

Conversational user interfaces (CUIs) such as chatbots "were created originally as attempts to simulate human conversations" [30, p. 20]. A CUI enables interaction (input and output) with the underlying dialog system also called conversational agent (CA) via different modalities such as speech, text and touch [27]. As conversational agents evolved, they gained popularity through Amazon's Alexa, Apple's Siri or Google Assistant and have been applied in everyday life to provide assistance in various contexts [28, 29]. In the past few years, conversational agents have been adopted in more domain-specific areas, such as improving mental health [30], helping with dietary changes [31] or guiding users in the finance sector [32].

Conversational agents are also used in various onboarding settings. In the university setting, a chatbot was implemented to support providing the information needed during the prematriculation phase [33]. Such chatbot-based approaches are also suited to take on the roles of a mentor or teacher, as proposed by Dominic et al. [34]. That proposal aimed to use a chatbot connected to Stack Overflow to relieve experienced programmers, who would normally be needed for onboarding new employees.

We conducted a preliminary empirical study [35] in a Fab Lab and identified a typical user journey of 3D printing newcomers. Based on these findings, we created an initial concept for a CA to support 3D printing onboarding. The concept covers four parts: general onboarding with explaining the printer and operating the printer divided into before, during and after printing. We refined this concept in the current study and implemented a sophisticated version of the chatbot.

3 PrintAssist

To explore the capabilities of a conversational agent for 3D printers, we used a human-centered design and research-through-design approach. We collected user needs and requirements in a series of previous studies on appropriation of 3D printers [8, 10, 11], during our long term collaboration with our local Fab Lab and its staff and community as well as from other related studies [23, 24, 26]. Based on the identified gaps, we created an initial concept (described in [35]) that was improved and implemented in this study. Throughout the design process, we placed a strong emphasis on user experience, making sure that the agent was easy to use and provided helpful and accurate information. In a final evaluation, we presented our conversational agent, called PrintAssist, to people with different levels of expertise in 3D printing to collect feedback, identify remaining issues, investigate the use of the agent and, in particular, capture what users write to the agent.

3.1 Concept and user journey

Our concept of PrintAssist encompasses a conversational agent that focuses on how to onboard novice home users to 3D printing. We focus on individuals at home because they often lack the support that newcomers receive from other (experienced) users in collaborative environments. As we know that onboarding in collaborative environments works quite well, we model our approach on the onboarding procedure used in our local Fab Lab. PrintAssist aims to simulate a 3D printing expert like a staff member of the Fab Lab for home users. To further detail the concept, we reconstructed a typical user journey of a novice who has no prior experience with 3D printing. This user journey is synthesized based on the related literature, several years of observations in our university's Fab Lab and conducting such introductions for newcomers.

Figure 1 illustrates some key phases of a typical user journey in the Fab Lab that we address in the prototype of PrintAssist. The first phase is called *Ice-breaking* (see Figure 1a). Persons unfamiliar with 3D printing often ask simple questions like "*what is this?*" The explanation from

(a) Ice-breaking phase

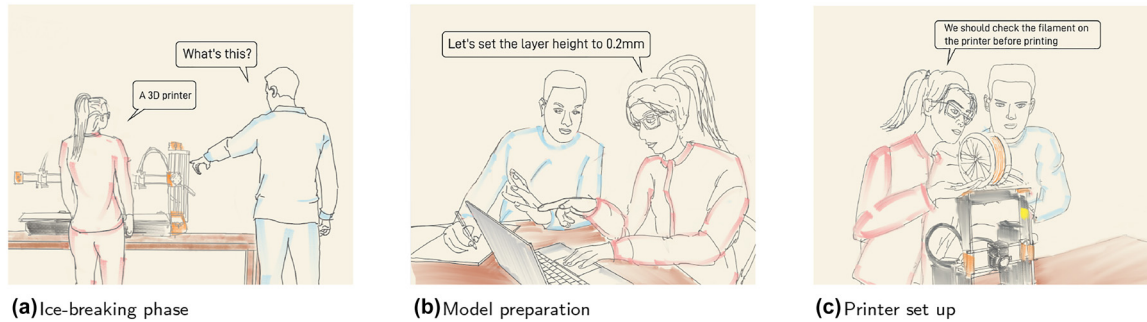**(b)** Model preparation

(c) Printer set up

Figure 1: Key phases of the user journey in the Fab Lab.

the expert is often a monologue, sometimes interrupted by follow-up questions from the novice. In PrintAssist, this phase is mainly about providing the user basic knowledge in a tutorial-like way.

The next key phase is the preparation of a print job, which is divided into acquiring a 3D model and preparing the model for printing (see Figure 1b). The 3D model of a beginner's first print job is often downloaded from popular platforms. In the next step—slicing the model—the beginners receive support from an experienced user to configure the slicing parameters. This phase is mainly about explaining and using the software tools involved in the workflow. Because all the different tools can be overwhelming for newcomers, PrintAssist should enable newcomers to start a print within a few clicks by integrating the functionality to download a model and slice it in PrintAssist. Furthermore, PrintAssist should provide an explanation of the chosen slicing parameters.

In the last key phase, the expert explains how to transfer the data to the printer, what should be checked before starting the print, and finally, starting the print (see Figure 1c). To replicate this, PrintAssist must be able to communicate with the 3D printer to upload the sliced model and start the print. PrintAssist also needs to ask the user if the printer is ready to use through questions like "Is the buildplate empty and clean?"

The concept includes further phases before and after the key phases mentioned above. For example, PrintAssist should inform the user about required maintenance of the printer and support the maintenance, offer to order new filament, document print jobs and share print configurations and results.

3.2 Implementation

The implementation of the presented prototype focuses on the key phases of the user journey. During the design of PrintAssist, we decided to use a chat-based interface

instead of a voice-based interface for our CUI as we needed to handle visual data like 3D models, images and videos. We used the instant messenger *Telegram* because it is used intensively by the community from which we derived the requirements. The main component of PrintAssist is the middleware that connects the other components (see Figure 2). The middleware receives all text messages from the user and passes those messages to Dialogflow, a natural language processing (NLP) service from Google, to detect the user's intention. Dialogflow's intention detection was trained on sentences collected during our observations in the Fab Lab, as well as sentences provided by the Fab Lab staff. Controlling the 3D printer is achieved by *OctoPrint* [36]. OctoPrint is an open source Python-based web application that brings the functions from the physical HMI into a web browser that then allows operating the 3D printer remotely. Octoprint is a well known and widely used software in the 3D printing community that is also used in our Fab Lab.

When a user adds PrintAssist to their contacts, PrintAssist will first introduce itself and gives a short overview of its capabilities (as suggested by [37, 38]), followed by a
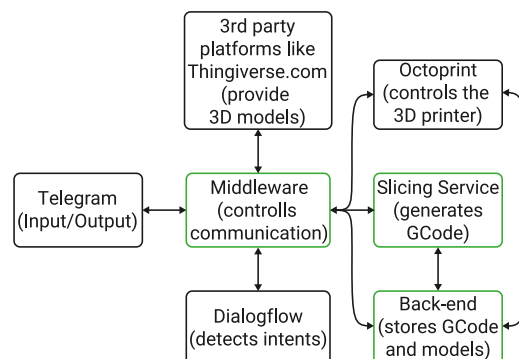

Figure 2: Overview of the software components involved in PrintAssist. All components communicate via REST APIs. The green marked components are developed by us.
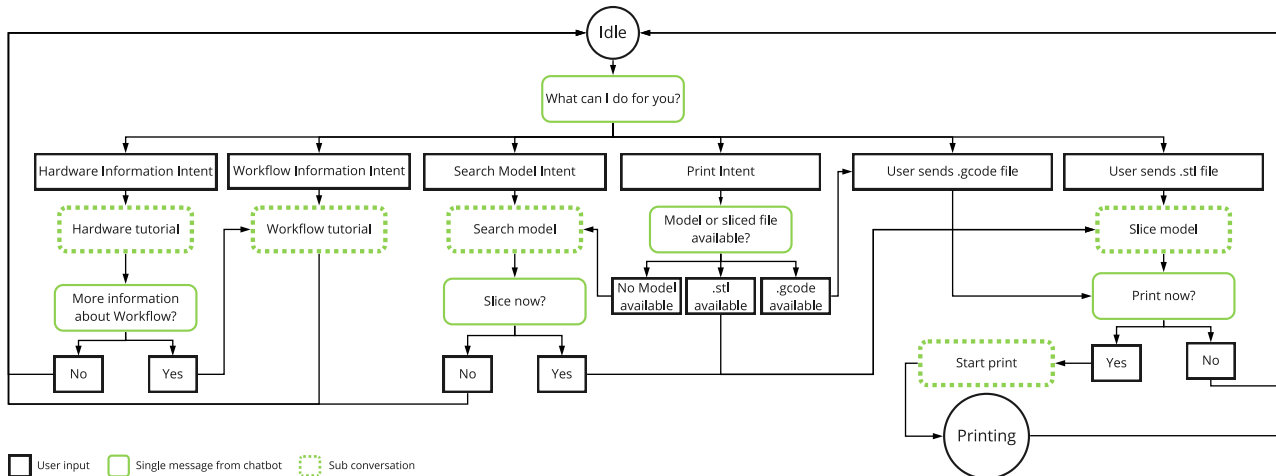
Figure 3: Simplified summary of the dialog structure.

"What can I do you for?" message. The chatbot is now in idle mode and waits for user input. At this point, the structure of the conversation is open, and users need to type what they want to do or to know. In the current implementation, the conversation can branch into five subconversations: (1) hardware tutorial, (2) workflow tutorial, (3) search model, (4) slice model, (5) start print (see Figure 3).

3.2.1 Hardware and workflow tutorial

Newcomers are often interested and curious about how the machine works. To address the ice-breaking phase of the user journey, we provide information about the machine and the workflow in two separate tutorials as subconversations. The subconversations can be triggered by phrases like *"How does the printer work?"* or *"How do I start a print?"* The explanations are divided into several steps, where each step consists of a text message with additional photos or videos. The text introduces domain-specific terms, while the images and videos provide the connection between the terms and the context. The messages are kept short, like a tweet (approximately 50 words), to help the user to keep track of the conversation. All messages from PrintAssist are currently hard-coded.

Each step of the tutorial must be confirmed manually by the user. We implemented two input types: (1) using natural language via the chat input to allow for confirmation words or phrases such as *"okay"* or *"go on"* and (2) predefined quick reply buttons [39] with the two options of *"Next"* and *"Cancel explanation"* (see Figure 4). We implemented both because we wanted to ease the interaction with PrintAssist during the tutorial by reducing the need to type *"okay"* multiple times and providing flexible interaction
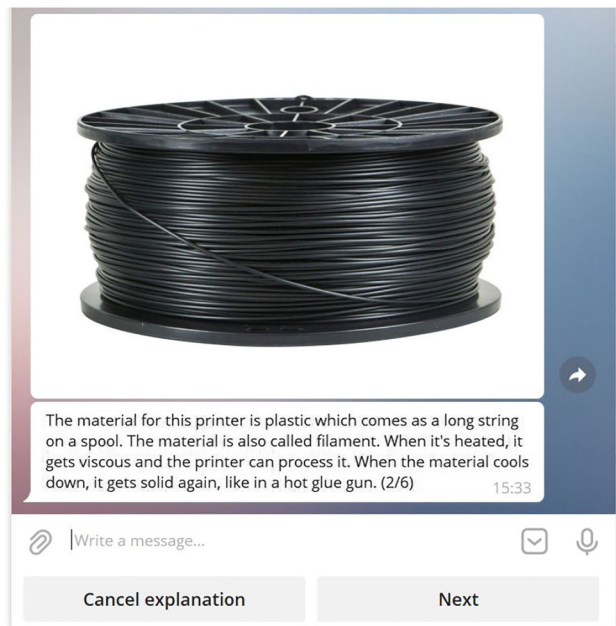

Figure 4: Explanation of the printing material.

with PrintAssist. By manually confirming the messages, the user always has full control over the pace of the tutorial. Each message in the tutorial ends with a progress indicator like "(1/6)" to show the user how much of the tutorial is already finished.

3.2.2 Searching a model

To reduce media discontinuities in the 3D printing workflow, PrintAssist provides the functionality to search for a 3D model inside the chat. The subconversation for searching for a model can be triggered by messages like *"Can you find a*

model for me?" or *"I am searching for a phone stand model."* If Dialogflow detects a search term like in the latter example (phone stand), PrintAssist will ask if the search term was correctly detected or not. Otherwise, PrintAssist prompts the user to enter a search term. After the search term is confirmed by the user, the middleware calls the Thingiverse[1] API. If Thingiverse has at least one object matching the search term, the number of results will be shown as well as a rendered image of the object (see Figure 5). We created a *carousel view* [39] by adding an *inline keyboard* below the image to navigate through the search results and select an object.

3.2.3 Slicing a model

PrintAssist provides an integrated slicing module to further reduce media discontinuity in the 3D printing workflow. With the slicing module, we want to address beginners, advanced users and experts. Therefore, we offer the following three modes: Enter parameters independently (for experts), Use preset (for advanced users), and Guided mode (for beginners). In the expert slicing mode, PrintAssist asks for specific values for any slicing parameter. The user can set the values by using the predefined reply keyboard buttons or through free-text inputs. In the guided mode, the user is not directly confronted with the parameters. PrintAssist asks for the desired result instead of the slicing parameters and calculates the required values itself (see Table 1). PrintAssist imitates an expert supporting a newcomer while setting the slicing parameters. However, PrintAssist explicitly asks these questions because PrintAssist cannot assess the model's properties.

After answering one question, PrintAssist explains how the selection will influence the slicing parameters. For example, when selecting a smooth surface, the chatbot

Figure 5: Searching a 3D model in PrintAssist (carousel view).

replies with *"For a smooth surface, I will set a thin layer height of 0.1 mm."* This way, we try to implicitly teach the users the relationship between slicing parameters and the printing results.

3.2.4 Starting a print

A print can be started in two different ways: (1) after the slicing process (see Section 3.2.3) or (2) by sending a Gcode file to PrintAssist. Before the print job can be started, PrintAssist asks the user if the printer is ready and offers help to beginners who do not know exactly what to check, such as whether the correct material is loaded and whether it is sufficient for printing. After the user confirms that the printer

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1 Thingiverse.com is a community-driven sharing platform for digital designs, specializing in 3D printing models.

Table 1: Questions and hints during the guided slicing process.

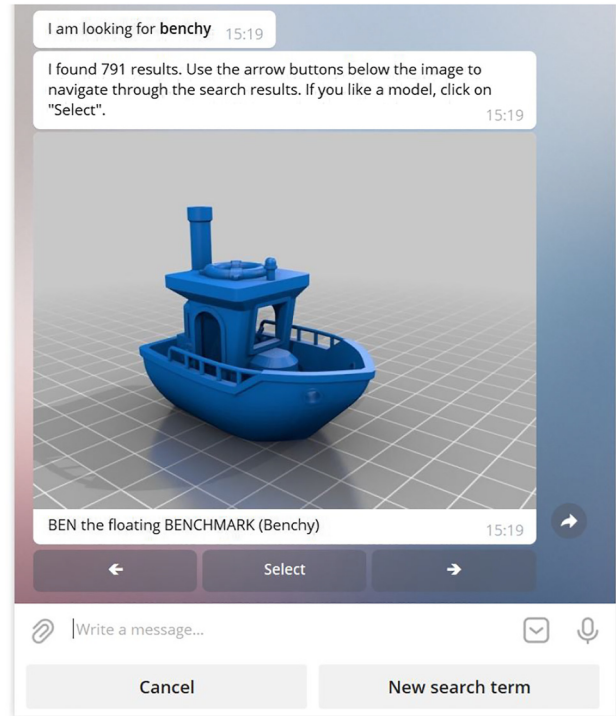| #	Question	Hint for decision making
1	Is this a test print?	Test prints are faster but lower in quality.
2	Do you want to have a smooth surface?	For a smooth surface, a thin layer height is needed. This will increase the print duration.
3	Does the object need to handle mechanical forces?	Decorative objects do not need to handle mechanical forces, but tools might. To handle mechanical forces, the object will be printed solid, which increases the print duration.
4	Does the object have fine details?	Fine details are, for example, indentations or bulges on the surface or threads on screws. The printing speed will be reduced for fine details, which increases the print duration.
5	Does the object have overhangs?	Overhangs are spots where parts of the model float in the air. Objects with overhangs should have support structures enabled. Printing support structures increases the print duration.

is ready, the middleware uploads the Gcode file to OctoPrint and starts the print. To keep the user updated, PrintAssist explains what is happening by telling, for example, that the printer is heating up and showing the rising temperature of the nozzle and build plate.

With its different subconversations, PrintAssist covers the basic information of 3D printing and provides implicit access to the components of the 3D printing workflow. Both the explanation and the tooling should enable newcomers to quickly start a print. Overall, PrintAssist tries to imitate a conversation with an expert. PrintAssist's behavior is reactive rather than proactive, and the capabilities are very utilitarian (cp. [32]).

4 Evaluation

To follow our human-centered design approach, we conducted an evaluation to collect feedback on the onboarding capabilities of PrintAssist from end users. Specifically, we were interested in (1) how users with different levels of 3D printing expertise would interact with the chatbot, (2) what users write and how they formulate questions, (3) how newcomers and experts rate the content and structure of the information provided in the tutorials and (4) whether Print-Assist enables newcomers to start a print independently. Therefore, we conducted a task-based evaluation. During the evaluation, the participants had to solve the following three tasks: (1) get to know the printer and the 3D printing workflow, (2) start a print based on a search term and a picture (including searching the model, slicing it, starting the print and asking for the print progress), (3) start a print based on a given Gcode file. The tasks were selected in the order that the users must use all available functions of PrintAssist. The detailed descriptions of the tasks are given in Appendix A.

Before the participants started the first tasks, we explained the evaluation process and asked for consent to record the session. To gain a clearer understanding of their impressions, we asked the participants to express their thoughts out loud and to describe their actions as they completed the tasks [40]. After the first two tasks, we did short interviews with the participants asking specific questions regarding their actions and other questions like *"How was the communication and interaction with the bot?"* or *"How did you like the provided information in terms of comprehensibility, quantity and structure?"* After the third task, we discussed their overall experience with the chatbot. At the end, we collected information about the participants' age, gender, profession, and prior experience with 3D printing, text-based chatbots, and voice-based virtual agents like Alexa or Siri.

Due to the ongoing COVID-19 pandemic, we conducted the evaluation remotely via Zoom. During the evaluation, we shared our screen with the participants. We placed the Telegram desktop application on the left side of the screen, and the right side of the screen displayed a PDF with the current scenario and task. Furthermore, we gave the

Table 2: Overview of the participants. The experience level *Novice* means that these users had no prior knowledge of 3D printing and only know about it, for example, from the media. *Beginner* means that these users only know very little about 3D printing or have already printed something under the guidance of other people. *Expert* means that these users know exactly how 3D printers work.

#	Age	Gender	Profession	3D printing experience
P0	36	M	PhD student	Expert
P1	29	M	PhD student	Novice
P2	31	F	PhD student	Beginner
P3	28	M	Student	Beginner
P4	34	F	Student	Novice
P5	26	M	IT-admin & web developer	Beginner
P6	28	F	User experience consultant	Beginner
P7	29	M	Engineer (vehicle construction)	Beginner
P8	22	F	Student	Novice
P9	27	M	Application engineer (robotics)	Expert
P10	28	M	PhD student	Beginner
P11	30	M	PhD student	Beginner
P12	29	M	Student	Beginner
P13	24	F	Editorial staff	Novice
P14	24	F	Student	Novice
P15	26	M	Student	Novice
P16	25	M	Web developer	Beginner
P17	30	M	Technical staff (Fab Lab)	Expert

participants remote control over the mouse and keyboard so they could independently interact with the Telegram application. This way, we did not exclude people without a Telegram account. We also had an additional camera connected to the video call showing the 3D printer.

In total, 18 people (6 women and 12 men) with an average age of 28 years (SD = 3.5 years) and varying professions and experiences with 3D printing voluntarily participated in the evaluation in August 2021 (see Table 2). On average, each evaluation session took 72 min (SD = 14.9 min; Min = 45 min; Max = 101 min). The participants were mainly recruited by public announcements via email lists and social media. After the first nine participants (P0–P8), we made two minor adjustments to PrintAssist: (1) We added the users' input as training phrases into Dialogflow to improve the intent detection, and (2) in the guided slicing mode, we added the hints to support the user's decision-making process. The overall structure of PrintAssist remained unchanged. Furthermore, we added the requirement that the object in the second task should be printed in high quality, forcing the participants into the longer path in the guided slicing mode.

5 Results

We present the results of both iterations of the evaluation in this section. During our interviews, most participants expressed that they enjoyed using PrintAssist and that they had a positive attitude toward the chatbot.

5.1 First interactions with PrintAssist

Participants exhibited many different behaviors when they first started to interact with PrintAssist. For example, P15 said, *"I don't know what to ask"* and needed to think for around two minutes while rephrasing his question multiple times before sending it. Other participants (P0, P6, P11) directly started the conversation by greeting the chatbot with *"Hi"* or *"Hello."* When the participants started to solve the first task—finding information about the printer and the 3D printing workflow—some problems arose. P5, P6, P7, and P8 first thought that they were talking directly to the printer, which influenced their question formulations. P5 asked, *"What can you do?"* and expected to read an explanation about the printer but instead received an overview of the chatbot's skills. Then he realized that he was not talking to the printer directly and rephrased the question.

For the start of the first task, we can group the participants by how many tries they needed to trigger the beginning of the explanation: (G1) could start on the first try—P0, P2, P10, P11, P15, P16, and P17; (G2) could start by rephrasing once—P1, P3, P13, and P14; (G3) could start after rephrasing up to four times—P5, P7, and P8; (G4) needed help from the moderator to find the right formulation—P4, P6, P9, and P12. Group 2 includes participants who just wrote one word, like *"explain"* (P13) or *"functions?"* (P3) and afterward, formulated full sentences. The participants in Group 3 used more specific questions, like *"What materials can you print?"* or *"How big can you print?"* (P7) or other questions that were not recognized by PrintAssist. After three unrecognized messages, P8 rephrased her question to match the wording of the greeting message from PrintAssist, which was then finally recognized correctly. We also observed that other participants adapted their formulations to the wording of the chatbot. The participants in Group 4 did not understand the given task and directly started the print procedure (by accident). P6 started with *"I would like to print something",* P9 wrote *"print,"* and P12 started with *"Search a Yoda figure for me."*

As described above, only four participants of the first iteration could start the tutorial within two messages. We discussed this issue in the interview after the first task. The participants said it was hard to start the conversation because some were overwhelmed by the whole situation or simply did not know what to say. However, the participants also had ideas about how to fix this, such as suggesting that the chatbot both provide an overview of the skills and give specific examples of how to trigger these functions in the greeting message. The additional training phrases added before the second iteration helped PrintAssist to understand the user's intention, resulting in seven of nine participants being able to start the tutorial subconversation within two messages in the second iteration.

5.2 Communication with PrintAssist

Arriving at the tutorial, most participants quickly noticed the reply buttons below the text input field (see Figure 4) and used them intuitively but also exclusively. Only P1 and P9 did not recognize the buttons, and both confirmed the messages from the chatbot with *"okay."* Later, P1 explained, *"I just did not notice [the buttons]; I was so focused on reading the text. It also felt natural to answer by text."* Two other participants were curious and typed in *"next."* Some participants (novices and experts) wrote follow-up questions to the presented information in the tutorial like P0: *"what is an additive manufacturing process?"* One expert (P0) stated that he asked the question to test PrintAssist, and a novice wanted to get additional information. Other participants stated during the task that they also had some follow-up questions but held them back for different reasons: P2 hoped that her

question would be answered later in the tutorial; P15 stated, *"I did not want to crash the bot"* even if everything worked correctly to this point. Because most participants only used the buttons during the tutorial, there were also statements like *"I find the interaction with the chatbot a bit one-sided"* (P2) or *"the interaction with the chatbot is boring because I just click next, next, next"* (P6). However, most participants liked the interaction with the buttons and made comments such as *"the buttons made the interaction easy"* (P4).

Nine participants mentioned the progress indicator at the end of each message in the tutorials. These comments were all positive, such as *"I like this x from 6. This way, I know how much I already completed"* (P2), but P11 added a side note *"[to see step] one of ten could be intimidating."* In regard to the content in the tutorial, all but two participants liked the division into multiple smaller messages and found the length of the messages appropriate. Especially the novice users mentioned that the information was easy to understand, and the tutorials made them more confident in using the printer. The participants also said the photos and videos helped them to better understand the related text as the images allow for more context. Overall, there were no major issues during the tutorial, and the participants described the communication and interaction with the chatbot as *"pleasant"* and *"guided."*

5.3 Download of a model

For the second task, searching a model by a given photo and name, slicing the model and starting the print, the participants first had to start the search procedure with a free text input similar to the start of the first task. All but one participant used one of the possible formulations to trigger the search procedure. P10 just wrote *"search"* and then changed his message to *"search model."* The other participants used similar phrases like *"I want to print"* (P0), *"print Benchy"* (P9), *"I want to print a model from the Internet"* (P1) or *"search Benchy"* (P5).

In the carousel view for the model selection (see Figure 5), P2, P3, P5 and P6 (all beginners) tried to move and rotate the model in the image to see if the model was the wanted model (which was not possible in this version) because the object was captured from a different perspective. Multiple participants mentioned that the search could become cumbersome quickly because only one model is shown at a time, and they argued for a gallery view with multiple models, like the presentation of the search results on Thingiverse.com. Using the arrow buttons to navigate through the search results was no problem for the participants.

5.4 Slicing with PrintAssist

When asked to select the slicing mode, 13 participants chose the guided mode, even though we told them that they could choose the mode based on their actual experience. Some experienced users mentioned that they were curious about the guided mode or were not fully confident in their abilities to continue without guidance, such as P11: *"I take the guided mode. It is a long time ago since I sliced something myself, and I cannot remember everything."*

Participants in the first iteration often struggled to answer the given questions (see Table 1). They were insecure about the consequences of the specific answers, and they relied on their intuition. They explicitly mentioned that some decision support should be given here. For the second iteration, we added decision support in the form of additional messages. These hints were perceived as very helpful by the participants of the second iteration, and they made their decisions very quickly and confidently. The participants also liked the possibility of hiding the hints. The indication of the print duration and the amount of needed filament is considered helpful, and some participants were surprised that even the small 3D Benchy could take quite a long time to print. Overall, the participants felt guided, and especially the participants from the second iteration felt confident that they had chosen the correct slicing parameters.

5.5 Starting a print job

Before the actual print can be started, the user must check that the printer is correctly set up. For this, the participants had to check the printer visually via the printer camera. Almost all novice participants expressed some uncertainty about what to check and asked the chatbot for help with the provided *"What do I need to check?"* button. With the help of the chatbot, all participants were able to start the print. Eight participants explicitly mentioned that they liked the live update, and P3 said, *"I feel connected to the printer due to the live data."* The other messages during the start were perceived as supportive, and the participants felt well informed. P2 said, *"I imagined the chatbot to be a person, like a nice grandpa, explaining what was happening."* Compared to the first task, the participants found the communication and interaction very pleasant and guided but a bit more interesting because their digital interaction had more impact on the physical procedure. Furthermore, it was noticeable that especially the novice and beginner participants had built some trust in the chatbot, as expressed by P2: *"he [sic] will know what he is doing."*

The participants had no problem solving the third task—printing a given Gcode file. All, except one, first wrote some kind of command to trigger the printing process. P8 directly sent the Gcode file without first sending a message. Other participants also thought about this but decided to first give a command and await the chatbot's answer because they *"didn't want to ambush him [the chatbot] with the file"* (P2).

5.6 Expert view and further improvements

During the closing interview, the participants rated the chatbot very positively. Especially the novice users liked the use of easy wording, pictures, videos and live updates/feedback. Most could imagine using only a chatbot to operate a 3D printer. Expert users like P0 and P17 saw the potential for novice users, but the experts would only use some parts of PrintAssist, like printing a Gcode file because, as P0 described, *"I believe I need more functions, especially during slicing."* Also, the other more experienced user stated the advantage of the chatbot for printing Gcode: *"Printing the Gcode was very fast and easy. It is better than using an SD card, going to the printer and searching the file on the small LCD"* (P6).

Even though the participants found the functionalities of the prototype extensive, some had suggestions and feature requests for PrintAssist: Tell jokes or give 3D printing fun facts, highlight important words in the messages, create an avatar for PrintAssist, suggest sample objects to print, create a print history, documenting and rating prints, and suggest maintenance and provide more help.

6 Discussion and lessons learned

6.1 Language, content and conversation

Natural interaction is generated by using a dialog-based conversation similar to real-life scenarios in a Fab Lab. NLP services like Dialogflow provide a suitable technological foundation to easily integrate NLP into applications. However, setting up this service was harder than it appeared at first glance. We invested a fair amount of work in creating training phrases for the system, but some of our participants still used different wording or other formulations. Our evaluation helped us gather more training phrases to make the NLP better. One finding is that the users adapt their formulations towards the formulation of the chatbot, and we suggest that this provides a good starting point when creating training phrases for NLP services. In addition, a few of our participants stated that they would use a more command-like way to interact with our bot. This might be related to the control purpose of PrintAssist and might be different for chatbots designed for coaching or entertaining [32].

Even though NLP plays an important role in our concept, PrintAssist only uses it in a few situations, such as starting the tutorials. Overall, we used a mixed approach of free-text input and button-based interaction. The reason for the free-text input, in combination with open-ended questions, was to make the interaction with the chatbot more human-like. However, we observed that this might not be the best solution for passive interaction, such as in the tutorials or when entering many parameters in the slicing process. By integrating buttons with predefined replies to these parts of PrintAssist, we limit the interaction possibilities in favor of usability and error prevention. We also suggest not disabling free-text input here as it might be used to ask follow-up questions or to ask for help.

When a chatbot like ours provides some high-level information, designers should be prepared for users asking follow-up questions. While creating the content of a chatbot, designers should think about what questions could arise about the presented information. A user could ask "simple" questions, like "what does this mean?" or more specific questions like, "How much does the filament cost?" In the first case, the conversational agent needs to keep track of the conversation to understand such contextual questions. Furthermore, both cases require a deep understanding and knowledge of the domain, and domain experts need to be integrated into the development of a chatbot [41]. Both cases impose challenges, and a chatbot designer should have a strategy to handle these situations, for example, by providing meaningful fallback responses or by integrating such questions into the NLP service.

The augmentation of physical artifacts with conversational agents raises questions about the agent's role. In our case, we think that representing a virtual third-party expert was the right choice, even if some participants first thought they were talking to the printer directly. A clear introduction of the agent and its role should prevent users from asking themselves "who am I talking to?" and would also define the boundaries of the system [32]. However, further research should investigate the influence of the agent's embodiment and representation. While starting an open conversation with PrintAssist feels natural, it can also create some challenges for users. As we have seen in the evaluation, this openness may overwhelm people and, therefore, requires a clear introduction that provides both the capabilities of the agent and how to activate those capabilities. A more proactive behavior of the chatbot could also improve this situation by, for example, actively offering an explanation about the printer.

6.2 Does PrintAssist make 3D printing an even bigger black box?

As Landwehr Sydow et al. [24] and Ludwig et al. [25] stated, 3D printers are often perceived as black boxes by the users. Dourish noted that people need to understand to some extent how a new artifact works to understand how to make it work in their practice [14]. Some researchers have already conducted studies to break up the black box of 3D printers to support the appropriation [10, 25, 42]. We are following this discourse, but one could argue that we create an even bigger black box with PrintAssist because we integrate more of the individual steps into our chatbot and hide the traditional workflow from the users. At this point, we argue that it is more important for the context of onboarding to provide a quick success moment for the user than to explain every detail to diminish the black box of the machine in the beginning. This quick success moment should make 3D printing attractive for newcomers and improve the users' self-confidence. Both should increase the likelihood that newcomers will use the printer regularly, which is a desirable outcome of an appropriation support tool.

We agree that for long-term appropriation, a deep understanding of the machine is essential, especially during breakdowns. However, the current implementation of PrintAssist deliberately addresses this only in a limited way by providing static tutorials.

With PrintAssist, we have introduced a functional CUI to ease the onboarding experience for 3D printing novices. PrintAssist serves as an HMI for 3D printers for novices and experienced users. In all scenarios, participants were successfully empowered to search and find a 3D model, slice it, print it, and view the printer's progress even without any prior knowledge of 3D printing. Based on participant statements, the level of confidence in one's own ability to start a print seemed to have increased substantially after using PrintAssist. However, due to our evaluation design, we were not able to measure this in a quantifiable way, nor did we aim for a comparison between PrintAssist and a traditional approach. We could observe that the trust in PrintAssist was also strong, in the sense that participants firmly believed that it would communicate properly with the printer and that everything would work out fine.

6.3 Reflection on the remote study

Due to COVID-19 restrictions during the evaluation period, the setup of our evaluation was highly artificial. As we know from the literature and our own observations, teaching novices how to use 3D printers is currently associated with embodied practice, physical interaction with the printers, being able to examine the machine from all sides and building muscle memory. Most of these aspects were not present in our evaluation setting. We tried to address this problem by providing an additional camera stream showing the printer from an approximately 1-m distance but with a fixed position. We are aware that this cannot replicate the experience of standing in front of the printer. However, PrintAssist was designed with the goal of enabling newcomers to be able to print an object as quickly as possible, and the evaluation showed that people without any 3D printing experience were able to print something even without being in the same room as the printer. Overall, there were no major issues while conducting the remote study. However, the setup had some impact on participant behavior (e.g., a few participants could not see the transmitted video of the printer correctly and verbally expressed the need to zoom in, as well as through non-verbal behavior by bringing their eyes closer to their screen).

6.4 PrintAssist as an HMI for 3D printers

At this point, we want to discuss the suitability of CUIs as HMI for 3D printers. Tasked-oriented CUIs are not too different from dialog-based wizards in normal graphical user interfaces. The main difference is that CUIs try to mimic a conversation between humans to create a more human-like interaction between humans and computers [29]. As we have seen in our observations in collaborative settings (cp Section 3.1), onboarding newcomers is often an intensive and individual procedure that takes place through a conversation between a newcomer and an expert. We see huge potential for CUIs in individual settings like at home, where newcomers do not have ready access to experts. Compared to tutorial videos or blog posts, CUIs allow users to ask questions and get answers immediately. In this case, it does not matter if the CUI is voice- or text-based. However, depending on the implementation, there are shortcomings. As we described in Section 3.2, we used a text-based CUI for PrintAssist because it would be hard to interact with a voice-only CUI when working with files, and it would be impossible to show images to the user. However, text-based CUIs also have limitations. For example, in PrintAssist, handling a large number of search results can be cumbersome (cp. Figure 5), and the possibility of observing a model in a 3D viewer is missing.

There are also positive aspects of a text-based CUI in an instant messenger app like Telegram. First, instant messengers are among the most installed apps on smartphones, and, therefore, users often do not have to create another account or install another app to interact with their 3D printer. Furthermore, due to the nature of the chat, previous

interactions are visible, and a user can scroll through the chat or use the built-in search functions to look for past events. In addition, using a chatbot makes it easy to share pictures of print results or failures that have been taken automatically taken by the printer.

The flexible input modalities (text, .stl, .obj or .gcode files) of PrintAssist do not force users to complete all workflow steps in PrintAssist. More advanced users can do the slicing on their PC and only send the .gcode file to PrintAssist to start the print job. Based on our working prototype of PrintAssist and our findings in the evaluation, we see especially text-based CUIs as suitable alternative HMIs for 3D printers and other machines.

7 Conclusions

As 3D printers increasingly appear in our private lives, questions arise about the appropriation of such devices in practice. The HCI discourse of appropriation support explores how concepts can be developed to support the development of usage practices around technologies. In our study, we turned to CUIs and explored how chatbots might ease the onboarding to 3D printing as a first step of appropriation. Based on the implementation of PrintAssist and our user study, we argue that chatbots can provide similar information as traditional manuals but in a more natural and interactive way. Hiding the different underlying tools makes it easier for novices to use a 3D printer. Our implementation showed that integrating common activities of the 3D printing workflow reduces media discontinuities and lowers the entry hurdles for newcomers. This enables newcomers to successfully start a print in a few minutes. Furthermore, providing sophisticated functions like slicing and remote controlling the printer makes PrintAssist also interesting to advanced users.

Presenting the most important information about the 3D printer in smaller blocks supported by photos and videos has been perceived as attractive and efficient by our participants. To ensure this information is provided in an appropriate way, it is very important to include domain experts in the design process. Furthermore, the embodiment and personality of the conversational agent play an important role in the conversation. The embodiment of PrintAssist as a third party between the user and printer seems to be appropriate for use as an HMI. Regardless of the embodiment, it is important that the chatbot informs the user who or what it embodies so that no communication problems arise.

Our evaluation shows that PrintAssist can both onboard novices to 3D printing and advance the practice of experienced users. The possibility of starting a print by sending the Gcode file to PrintAssist was perceived as most useful by the advanced participants as it makes transferring the data to the printer easier compared to traditional methods.

Although our study has a rather exploratory character, we argue that we make an important contribution to how conversational agents can be used as an onboarding modality to ultimately support the appropriation of complex systems such as 3D printers. We hope to inspire both researchers in the field of appropriation research and interface design and practitioners of 3D printing to approach and explore such new forms of interaction.

Appendix A: Evaluation

We provide the descriptions of the evaluation scenarios given to the participants in the following subsections.

A.1 Introduction and first scenario

You are a hobby craftsman and like to tinker. You received a 3D printer as a gift for your birthday. You unpack the 3D printer at home (it's ready to go), and you see an instruction leaflet with the following content:

This 3D printer has an interactive Telegram chatbot through which you can learn more about this printer and also operate the printer. Search for @PrintAssistBot in Telegram or scan the QR code to add the bot to your contacts.

You have successfully added the bot to your contacts, and the conversation will start. Because this is your first 3D printer, and you also don't have that much experience with 3D printing, you first want to learn more about the 3D printer and what you need to do to start a print.

You try to solve this task with the help of the chatbot.

A.2 Second scenario

A.2.1 Part one

You were at a friend's house a few days ago and saw this model (picture below) there, and you liked it very much.

Now you want to print the model yourself. Your friend told you that you could find the model under the search term **Benchy**.

Your task is now to find the model with the chatbot and then print it out in high quality.

A.2.2 Part two

The printing process is now running. You've seen that the printing takes quite a long time, and you don't feel like standing next to the printer all the time. You decide to go to your living room (the printer is in your office) and watch some Netflix. After a while, you are curious and want to know what your printer is doing. Because you just made yourself so comfortable on the couch, you try to get information about the current progress of the print via the chatbot.

Your task now is to retrieve the progress of the print.

A.3 Third scenario

A friend of yours is having problems with her own 3D printer and needs to print a spare part. However, that's not possible with her printer right now. She asks you to print out the spare part for her. Of course, you are happy to do so. Your friend has the same printer as you, and she prepares the model for printing and sends you the finished Gcode file so that you can print the file directly.

Your task is now to print the file via the chatbot.

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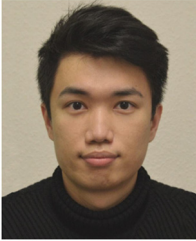
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