Smart Makerspace: An Immersive Instructional Space for Physical Tasks

Jarrod Knibbe[1,2], Tovi Grossman[1], George Fitzmaurice[1]

[1]Autodesk Research, Toronto, Canada
{firstname.lastname}@autodesk.com

[2]University of Bristol, UK
Jarrod.Knibbe@bristol.ac.uk

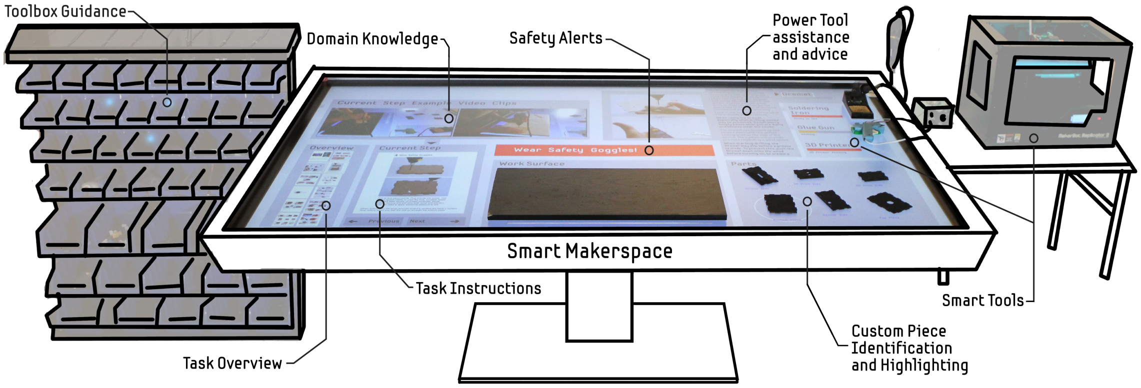

Figure 1. The *Smart Makerspace*. Focused around a smart workbench, toolbox and power-tools, the *Smart Makerspace* provides an immersive, integrated instructional experience for novice makers.

ABSTRACT

We present the *Smart Makerspace*; a context-rich, immersive instructional workspace for novice and intermediate makers. The Smart Makerspace guides makers through the completion of a DIY task, while providing detailed contextually-relevant assistance, domain knowledge, tool location, usage cues, and safety advice. Through an initial exploratory study, we investigate the challenges faced in completing maker tasks. Our observations allow us to define design goals and a design space for a connected workshop. We describe our implementation, including a digital workbench, augmented toolbox, instrumented power-tools and environmentally aware audio. We present a qualitative user study that produced encouraging results; providing features that users unanimously found useful.

INTRODUCTION

Do-it-Yourself tasks (DIY) and 'maker' activities are supported by a wealth of instructional resources online. Websites such as Instructables[1], Make[2], and IkeaHackers[3] provide guidance across a broad range of topics, through illustrated walkthroughs similar in style to traditional paper manuals. However, research on tutorial systems for complex software highlights the benefits of a more integrated and multimedia-based instructional experience [3, 5, 6, 9, 11].

We suggest that there are similarities between the difficulties faced in using complex software systems and completing DIY tasks. These include: uncertainty over tool location, correct tool usage, and steps required to achieve a goal. In a DIY 'maker' task, these concerns are further emphasized as actions are often irreversible and procedures may be dangerous. Based on these similarities, we draw on software tutorial research to develop an instruction-delivery and training system for DIY maker tasks. [1][2][3]

In this paper, we present the *Smart Makerspace*; a context-rich, immersive instructional workspace for novice and intermediate makers. The Smart Makerspace is designed to provide an informed and safe environment in existing machine shops and maker spaces where initial maker skills can be learned and refined. Although the maker community emphasizes peer learning, this occurs not only in-situ, but through a 'build and blog' spirit and active online community [20, 23]. Our work seeks to bring this online material 'to-life' within the physical environment of making. Through augmented tools and surfaces, the Smart Makerspace can monitor, record and respond to makers' physical actions in real time. This 'smart' approach provides opportunities for workflow monitoring and the delivery of interactive tutorials. The environment also presents an opportunity for automated recording [2]. However in this paper we focus on the *delivery* of a

ITS '15, November 15-18, 2015, Funchal, Portugal

DOI: http://dx.doi.org/10.1145/2817721.2817741

---

[1] www.instructables.com

[2] www.makezine.com

[3] www.ikeahackers.net

context-rich, multi-faceted instructional experience for a single novice or intermediate level maker.

In the first step of our research, we performed an observational study of the difficulties faced within makerspace practice and the differences between novice and expert makers. Based on these observations we define the design goals of our system and present a hardware design space. We then present the *Smart Makerspace* (Figure 1). Our makerspace delivers detailed task instructions through a manual, a workflow overview and task- and skill- based videos. Tracked power tools enable tool status monitoring, in turn providing tool readiness, usage information and time-relevant safety advice. An augmented 47-bin toolbox gives tool location cues and environmentally aware audio feedback provides task progress and safety warnings. Finally, we report on an observational study in which participants responded positively to the features of our makerspace.

RELATED WORK

Current Instructional Practices for Physical Tasks

Previous research has explored the resources used for physical tasks [26–28, 30]. The online maker/DIY communities are by far the most popular source of instructions and guidelines [27]. While instruction sets are available on a wide range of topics, individual instructions typically focus on: introducing a specific skill; or providing a guide to building a specific item [26, 30]. Within this, some instructions provide detailed background and debugging information, where others focus on the fewest steps to complete the task [28]. These different styles necessitate continuous research and content switching in order to complete a task, distancing the user from the original task itself [27, 30]. Wakkary et al. suggest the creation of instruction sets based on the principles of interaction design [30] and our work could be considered one such example.

Research has also highlighted the importance of task feedback [29]. While feedback is available online, through forums and comments, this adds a further time-cost overhead to the learning process [29]. With the *Smart Makerspace* we bring the differing types of instruction sets together, such as skill-based instructions, task-specific guidance, and variations in possible approaches.

Delivering Software Tutorials

Similarly to physical task instructions, software tutorials are abundant online. However, instructions and tutorials can also be integrated within the software itself [3, 6, 9]. This can allow for a more relevant and immersive learning experience. For example, with ToolClips [5] users are provided with tool-relevant videos during system use. Pause-and-Play [17] provides time-relevant information by synchronizing video assistance with a user's task progress.

Beyond providing relevant cues, software tutorials can also provide system guidance and facilitate learning from experts. In Sketch Sketch Revolution [3] and Stencils-based Tutorials [9] the user is guided through a task, whilst the system highlights the correct tools and configurations to use, and reduces opportunities for error. Grabler et al. [4] and MixT [1] both demonstrate systems that automatically produce tutorials and guides from expert user demonstrations. In Chronicle [6] and Community Enhanced Tutorials [13], users can explore a system based on the execution of experts, viewing how tools were used, how processes were combined and how end goals were achieved.

We leverage and adapt these principles within our Smart Makerspace to provide a learning environment that seamlessly combines digital and physical environments.

Immersive Physical-Task Environments

Previous work has explored the use of in-situ and contextual cues for performing tasks in physical environments (e.g. [16, 25]). A popular approach within this work is the use of projection for augmented walls and surfaces [10, 16] and overlaid graphics [14, 29]. Beyond projection, real-time systems have attempted to place a remote expert in the scene [7, 21, 25]. In this, the requirement for constant expert presence makes this unsuitable for an amateur or personal makerspace.

Augmented reality systems have been developed to assist with physical tasks. Henderson et al. [8] built a head-mounted display providing detailed overlaid graphics to assist complex airplane engine mechanical tasks. Similar techniques have been used in other settings, including automotive manufacture [18] and Lego building tasks [24].

The work of Henderson et al. is close to ours, yet we believe that our approach is the first of its kind. While Henderson's work focuses on the psychomotor phase of a procedural task, our work looks at high-level tasks in which multiple steps must be performed, and a variety of new skills and tools must be learned.

ELabBench [22] provides a digital benchtop for biological experimentation, bringing a wide range of desktop computing capabilities into the sterile laboratory environment. ELabBench supports the annotation of test tube racks, note taking, web browsing and document editing. Our work is complementary to this and builds on its core principles. ELabBench focuses on personal recording during a physical task, where our system is instructional, actively monitors and feeds-back on the status of tools and materials in the wider environment and focuses on content delivery. We draw inspiration from a range of 'smart' tools previously presented by the HCI community (such as [31–33]) to augment existing tools and facilities across an entire space, thereby seeking to better support a maker throughout the entirety of their practice.

OBSERVATIONAL STUDY

To better understand the intricacies of practice within maker and DIY tasks and to derive requirements for our system we conducted an exploratory think-aloud study with both novice and expert makers. We explored the online maker communities and referenced the Makerspace Playbook [15] (an educational guidebook) to gain an understanding of the types of tasks performed by makers. From this, we designed a ‘hello world’ style maker project which consisted of a box with lights that blinked when an object approaches (Figure 2). Our intention was to incorporate a range of tools and skills popular within this domain (including electronics, drilling, soldering and 3D printing), to provide a broad base from which to explore the challenges of making and motivate our work. Although an ethnographic observation may have highlighted further nuances of practice, our generalized task served to provide generalized observations to drive our prototype’s design. The box consists of 6 side pieces, housing a proximity sensor, 2 LEDs and a Phidget. We authored a 13 step *Instructable* entitled “Proximity Box”, which can be viewed on the *Instructables* website[4]. While websites such as *Instructables* support videos within their instructions, the majority of sets (~95% on *Instructables*) consist solely of text and images. As such we did not include video, to allow us to understand the challenges users encounter with the most typical style of instruction sets.

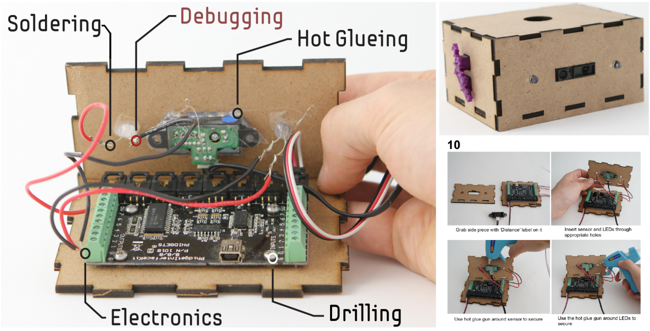

Figure 2. The ‘Proximity Box.’ Clockwise from left - breakdown of different skills, finished box, example of step.

Participants

We invited 8 participants (3 female, age: M=28, SD=5.5 years) to build our proximity box. The participants rated their skill and experience levels (3 beginners, 2 intermediate, 3 experienced) and provided examples of projects completed, including: building IKEA furniture, home improvement DIY and personal robotics. Three participants described themselves as tinkerers or makers. Five participants had done educational courses (primarily during college) or online research to improve their maker skills (primarily through online forums and Youtube). While five participants suggested they used online tutorials for new tasks, only 3 participants said they like to read a manual when conducting a DIY task.

We invited both novice and expert makers to take part in this study in order to highlight the differences in their practice. Furthermore, our intention was to design a system that could be integrated into existing maker spaces, thus the system would need to support expert and novice use alike.

Apparatus

The study took place at a workbench. The bench was equipped with a 3D printer, glue gun, soldering iron, rotary tool and protective surface for drilling. A laptop was provided for viewing the *Instructable*. Behind the participants was a 47-bin toolbox that contained all other components needed for the task. Of the 47 bins, 17 had parts necessary for the task. The participants were recorded with 2 video cameras, one focused on the workbench and the other focused on the toolbox.

Procedure and Design

The participants completed a questionnaire prior to beginning the task, including questions relating to their skill, experience and confidence with different tools. The users were then instructed to build the box, following the *Instructable* as closely as they wished, while vocalizing their thoughts. The participants were allowed to look for additional resources online. The building-tasks took approximately 1 hour to complete. An experimenter was present to take notes on their spoken thoughts, the details of their actions and to carefully monitor the situation for any safety issues. The users were instructed to complete all steps to the best of their abilities. Help was only provided to participants who had previously attempted a step and then asked for help or when safety concerns arose. Upon finishing, users completed another questionnaire regarding their strengths and weaknesses with the building task.

Observations were analyzed to highlight recurrent themes across the participants relating to making.

Challenges Encountered

Here we will focus on four principal issues which arose during our study: an overview of the task, domain knowledge, tool selection and tool usage details.

An Overview of the Task

Inexperienced makers followed the instructions precisely, often on a per sub-step basis, without any understanding of (or interest in) the wider task. This reluctance to explore the task further made it difficult to resolve issues that arose. As an example, at one stage the maker prepared two lengths of wire, though the required lengths were not given. Those with more experience knew to look further ahead into the instructions to determine the wire’s purpose and thus calculate its length, whereas those focused only on the precise step guessed.

In general, the experienced participants were keen to see an overview of the build so they could proceed with a more personally-driven execution.

‘I think if I saw the overview of the whole project, rather than step-by-step [instructions], I would have completely ignored the instructions and just tried to ‘Macgyver’ it together. At least with the physical box, the electronics, which I am less comfortable

---

[4] http://www.instructables.com/id/Depth-sensing-Box/

with, I probably would have gone back to figure out what was going on there.' (P2)

This understanding of the wider task also allows expert makers to know where they can 'cut corners.' For example, when referring to a step which required securing bolts to be fitted, P7 said: *'Now I'm only using 2 because I hate putting bolts on.'* Similarly, in order to save time, P2 chose to glue the circuit board into their box as opposed to using the suggested drill.

Domain Knowledge

Another clear divide between participants in our study was over domain knowledge. The more experienced makers continuously referenced prior experience '*I would normally put [the Dremel] in reverse to make sure it's tight'* (P5) or '*I do know you are supposed to sort of curl the end of the wire around the end that you are soldering to'* (P6). In another example, those with more experience soldering would look for support tools (e.g. a 3rd hand) or additional components (e.g. heat shrink) to help them complete the task. In this instance, domain knowledge could also be used to confirm whether the soldering was 'good enough.' However, this required additional background knowledge that the novices did not share, affecting their confidence throughout the build.

Tool Selection

An important function of a 'makerspace' is the variety of different tools that are available and the uncertainty surrounding correct tool selection. Our makerspace has a 47 bin toolbox, holding a variety of different components including: different sized screws, transistors, LEDs, screwdrivers, wires, drill bits etc. A toolbox of this size is not unusual and, regardless of experience, all participants spent a significant amount of the total task time looking for tools. While expert makers could confidently select an appropriate tool once located, novice makers also struggled with the selection process as many tools appear similar.

Tool Usage

During the task participants used three power tools: a rotary tool (Dremel), a soldering iron and a glue gun. Each of these tools presents its own set of challenges, for example a drill can slip and toxic fumes are produced when soldering. While more expert users are accustomed to these hazards (e.g. P1 knew to exhale when soldering), they are an important concern for novices. P3, P6 and P8 were all concerned with whether they were using the Dremel tool correctly and whether their technique posed any danger. Upon starting drilling, P8 asked: *'Am I being safe?'*

The participants demonstrated varying levels of awareness of the tools around them. For example, some participants would meticulously tidy after every stage, ensuring tools were turned off and their workspace was clear, where others would neglect tools once they were done with them – leaving soldering irons and glue guns turned on. While perhaps not an immediate risk during a short build, these risks can become more serious when partaking in a longer or multi-participant build.

Discussion

Our observational study has highlighted some clear differences between novice and expert makers that our system can aim to address.

Firstly, an important aspect of making is understanding an overall aim and then attempting it personally based on prior knowledge. It is through this individuality that makers express their creativity and derive their enjoyment. This, in turn, is what sets making apart from standard, result-oriented DIY tasks. Secondly, prior knowledge helps problem solving and provides the confidence to multi-task, use different tools, add personalization to a build or divert from the instructions. Novice makers do not have this corpus of knowledge to draw upon and are thus more constrained by the bounds of the instructions.

Novice makers display more risk aversion and uncertainty over tool usage and tool selection. Both through past experience and a greater understanding of different tools, expert makers are more confident, adaptable and safer in their practice.

Additionally, the usage of the laptop within the study provides an important insight for the design of our makerspace. As a laptop affords similar freedom of movement as a paper manual, we had expected to see a similar attitude to its use, such as repositioning for the most un-obstructed view and carrying to the toolbox for direct tool reference. Instead, participants clearly oriented themselves around the laptop, bringing work surfaces and tools towards it, making the laptop, and by extension the digital manual, the key anchor within the space. Whilst this orientation may have been for a number of reasons, including damage limitation, it highlights an important consideration when designing 'expensive' technology into a workshop environment. Any novel technology should be positioned to encourage maker participation.

DESIGN GOALS

In this section, we outline the design goals for our Smart Makerspace. These goals are derived from the observations from our study and the lessons learned from research on software tutorial systems.

D1. *Provide an Overview.* Our study highlighted the potential benefits of providing a task overview. This encourages a wider exploration of the build, assists in problem solving and supports personalized approaches.

D2. *Provide domain knowledge.* We have shown that prior knowledge plays a significant role in the successful completion and enjoyment of a maker task. Our system should showcase different methods and practices for completing the given task as a proxy for missing domain knowledge. This helps to teach and inspire [11, 13], while generating community spirit [23].

D3. *Limit the opportunity for error*. Our study demonstrated the importance of confidence in tool selection and usage. Building upon research in software tutorials, which guides the user towards intended tools and locations [3, 9], our system should inspire maker confidence through clear information on tool locations, usage and practice.

D4. *Provide clear spatially- and contextually- relevant instructions.* Our study showed that during the execution of specific skills, our participants focus changed between task-based and skill-based. Similarly to Chronicle [6], our system should support both of these focuses, allowing a maker to progress, knowing that relevant help will always be provided.

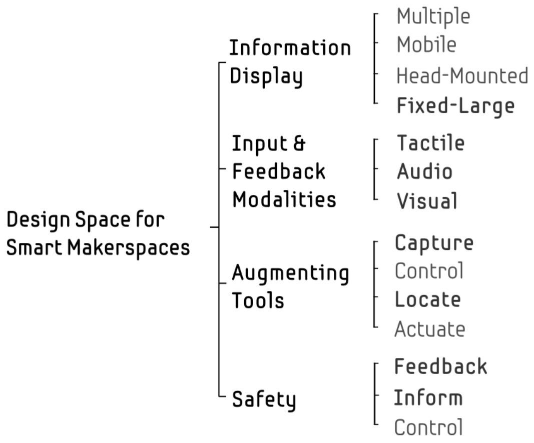

Figure 3. Design Space for Smart Makerspaces. (Emboldening highlights features used in our Smart Makerspace).

DESIGN SPACE FOR SMART MAKERSPACES

Here we explore the hardware design space that can enable our design goals (Figure 3); presenting a variety of the opportunities and motivating the decisions that we made. This is not intended as a full taxonomy, rather a subset of the possibilities most relevant to our work.

Information Display

As we move towards a connected, smart makerspace, we encounter opportunities to display varied information. We define four scopes of display: *multiple*, *mobile, head-mounted* and *fixed-large*.

Maker tasks frequently take place across a range of different locations within a space, for example separate woodwork, metalwork and electronics spaces. As such *multiple displays* could be used to provide area-relevant information. *Mobile displays* could provide similar functionality, while replicating the affordances of traditional paper manuals. Makers could 'dock' their device at different stations within a makerspace, thus triggering appropriate resources. *Head-mounted displays* could be used to provide view-specific overlays or peripheral information [8]. These devices provide the greatest opportunity for continuous or 'always on' instruction.

From our experience, makerspaces are typically based around a central 'construction' zone. This fixed central location supports the use of a *fixed large display*, which encourages a maker to research a task or skill before proceeding to practice what they have learned in the different zones. A *fixed large display* could be positioned as a smart workbench [22] or be located on a wall. The display could be projected or make use of a large screen. As a result of the usage style of the laptop in our observational study and the benefits of a clearer co-location of workspace and information display [12, 19], we adopt a fixed large display as a workbench in our makerspace. We chose to use a tabletop screen to mitigate the risk of occlusion from participants leaning over the work surface (as we observed in our observational study). Although large screens may seem a less feasible technology than projection today due to damage risks, there is good reason to believe such displays will be ubiquitous and damage resistant in the future[5]. That said, a projector based system could be similarly implemented without impacting the overall design principles and spirit of our work.

Input and Feedback Modalities

As making is a manual activity already including significant *tactile* action and feedback. We suggest the use of *audio* feedback, alongside *visual* display, to enrich the feedback experience. This could encode spoken feedback or simply provide a prompt to retrieve information from a display. Similarly, *audio* and *visual* input could be used alongside tactile action to drive the system.

Augmenting Tools

Across smart tools there are opportunities to *capture*, *locate*, *control* and *actuate*. Tool information can be *captured* to know when and how a tool is being used. Tools can be *located* such that the system can guide a maker towards them. The system could *control* the tools use, for example automatically disabling or setting its speed where appropriate, or *actuate* tools, automatically performing tasks with them.

Safety

Safety information can be provided to *feedback* to or *inform* the maker or to *control* the situation. Given system knowledge of a tool's current state, *feedback* could alert the user to wear safety goggles and the user could be *informed* of relevant safety information. Should the safety glasses not be worn, the system could disable the tool (*control*).

THE SMART MAKERSPACE

We developed a prototype Smart Makerspace, delivering an integrated instructional experience for a single maker in existing public or private machine shops and maker spaces (Figure 1). The system can be divided into 3 main components: an augmented workbench, instrumented power-tools and an instrumented tool-box. As we describe

---

[5] www.corning.com/ADayMadeofGlass

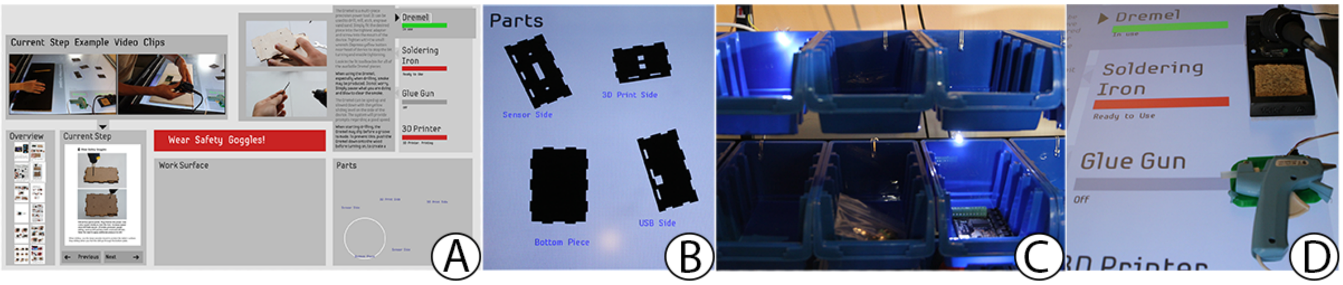

Figure 4. Layout and features of the Smart Makerspace. A: workbench layout, B: custom piece tracking, C: toolbox guidance, D: augmented power tools.

our system's features, we indicate in parentheses the relevant design goals they address.

Augmented workbench

We use an 84-inch, 4K digital whiteboard on a horizontal stand. We chose a display of this size as there is adequate space to provide a wealth of information alongside a traditional workspace.

We placed a 3mm sheet of transparent acrylic over the display to prevent scratches. An additional wooden block marked the intended workspace and added further protection for drilling and soldering. We mounted a depth-sensing camera above the display to enable object tracking and touch interaction. Any sensors used were interfaced to the central desktop computer using Phidgets USB interfaces.

The Dremel (precision rotary tool), soldering-iron and glue gun are positioned on the workbench. Due to its weight, the 3D printer was placed on a side-table.

Manual

The augmented workbench experience is based around an illustrated manual - providing the exact same information as the *Instructable* used in the pilot study. Below the manual there are soft-buttons to enable navigation between steps (Figure 4a, bottom left).

Overview

Beside the manual is an overview of the task, containing a thumbnail of every step (Figure 4a). The overview provides a quick reference for the sequence of subsequent steps and is designed as a cue to encourage the exploration of the entire manual (*D1*).

Previous user's videos

Above the manual are videos of other users performing the current task (Figure 4a)(*D4*). These videos provide additional cues to the images in the manual, assisting with trouble-shooting and demonstrating the variation in approaches to completing the manual tasks. The videos are intended to provide novice makers with broader knowledge of a current task. As our instruction set was manually configured, the user videos were captured from the side. However, in the future these videos could be captured from above, to provide first-person view. Additional information is also available in the ToolClips (explained below).

On-table Tool Prompts

The power-tools required to complete each step are highlighted on the table (*D3*) (Figure 4a). The table prompts users to turn on/off relevant tools either before they are needed or once they have been used. Additional information about the current status of tools is also provided, for example the status of the 3D printer (i.e. 'printing') or the soldering iron ('hot, ready to use') (*D4*).

ToolClips

When a tool is to be used, relevant ToolClips are displayed (*D4*), including both text and video. For example, if a soldering iron is to be used, an explanation of its use is displayed, including best practices, safety tips and troubleshooting advice (Figure 4a). These tips are purposefully positioned near the workspace, such that they are easy to follow or refer to when using the tool.

Custom Piece Highlighting

Beside the work surface, our system tracks, highlights and identifies custom pieces required for a build (Figure 4b) (*D3*). From our exploratory study, we found that the custom pieces caused the most difficulty amongst participants as they are unique to the build and thus no prior knowledge can be referenced. Using visual highlighting, the pieces required for each step are uniquely identified and annotated.

Environmentally Aware Audio Feedback

The system provides *positive* and *warning* audio feedback based on a number of different events (*D3*). The system provides a *positive* audio tone for correct tool usage (i.e. once the 3D printer has been turned on), when a process is complete (i.e. printing finished) or a tool is ready for use (i.e. glue gun heated). The system provides a warning tone and corresponding visual cues should safety glasses be needed or if a tool is used incorrectly (i.e. the drill being used faster than a given speed). The volume of the audio alerts is dynamically adapted to account for any tools that are being used. For example, the tone alerting that the drill is being used too fast is significantly louder (to account for the sound of the drill) than the tone reminding the maker to wear safety glasses when removing the soldering iron from the holster.

Augmented Power-tools

We have equipped our makerspace with four 'power tools/devices': a 3D printer, a precision rotary tool (Dremel), a soldering iron and a glue gun (Figure 5). These tools were chosen as representative of those routinely used in maker and DIY procedures. Each of these tools is instrumented such that the system knows its current state and location, can provide feedback on its use and can remind users to turn tools on/off according to task instructions (*D3, D4*). Here we detail the instrumentation of the tools as examples of possible instrumentation techniques, not necessarily as best case sensor scenarios.

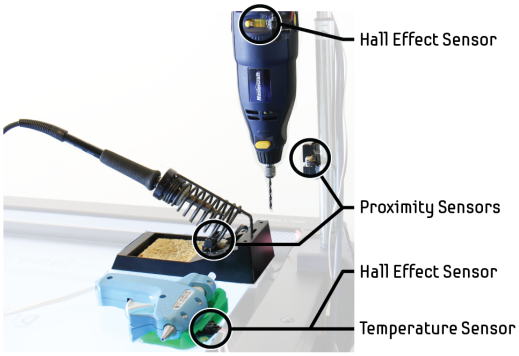

Figure 5. We augmented power-tools with sensors to monitor their state and usage.

Soldering Iron - The soldering iron has a precision light sensor placed over its power light. As the light can be off (indicating tool off), constant (heating) or flickering (ready), the system can infer its state. A proximity sensor is placed beneath the iron's holster, such that the system can determine whether the iron is present or has been removed.

3D printer - The 3D printer has a voltage monitor attached to its power cable. The system can identify when the printer is on (low-constant voltage), heating (medium, fluctuating voltage), printing (high, fluctuating voltage), and finished (low constant voltage).

Precision Rotary Tool - The Dremel has a hall-effect sensor and a magnet attached to the variable power switch (Figure 5). This allows the system to know the state and speed of the Dremel and thus enables feedback regarding required, suggested, or safe, speeds. The Dremel stand houses a proximity sensor so that the system knows when the tool is present or has been removed, allowing for additional relevant safety prompts.

Glue Gun - The glue gun has a custom 3D-printed holster that includes a temperature sensor, which enables the system to know the state of the device (Figure 5). A hall-effect sensor and magnet lets the system know when the device is present in the holster.

Instrumented Toolbox

We instrumented the 47 bin toolbox such that each bin is equipped with an LED (Figure 4c). The system triggers these LEDs to guide the maker towards the correct toolbox bins needed for each step of the manual. By clearly indicating the correct tool locations, the system can significantly reduce the uncertainty of novice makers when selecting tools for a task (*D3*).

EVALUATION

We conducted a qualitative think-aloud user study to evaluate the initial design and features of the Smart Makerspace.

Participants

We recruited 8 new participants to conduct a maker task using our system. The participants (2 female, age: M=35, SD=9 years) rated their skill and experience levels (3 beginners, 3 intermediate and 2 experienced). We chose to include a range of experience such that we could assess differences in practice and explore our makerspace's ability to scale between users. Similarly to our observational study, previous experience involved tasks such as home renovation, personal robotics and musical instrument making. One participant described themselves as a maker and 6 participants suggested they enjoyed 'making' tasks. 3 participants stated that they like to read manuals when building something and 5 participants said they used online tutorials. Five participants had previously used the *Instructables* website.

Apparatus

The participants used our Smart Makerspace. The system was manually configured to provide instructions for the same box as used in our previous study. The participants' were recorded on a video camera that encompassed the workbench, the 3D printer and the toolbox. An experimenter was present to take notes on the participant's thoughts and actions.

Procedure and Design

Before beginning the build, the participants completed a questionnaire about their previous maker and DIY experience. They were then given a 3 minute introduction to the makerspace and its features. After the introduction, the participants were asked to use the system to build the proximity box.

Upon completing the build, the participants filled out another questionnaire. For each individual feature of our system, the questionnaire asked them to rate, on a 5-point Likert scale, the statement 'I found it useful' (1 = strongly disagree, 5 = strongly agree).

Quantitative Results

Overall, participants genuinely enjoyed using the Smart Makerspace, giving an average enjoyment score of 4.75 out of 5 and were keen to conduct other similar tasks in the future. Participants gave our table on average 4.38 for usefulness. Based on user responses, the most useful features of our table were: the toolbox highlighting, as it enabled quick tool locating; the safety goggles warnings, as a timely reminder; and ToolClip Text, as a tool walkthrough, helping those unsure about specific tool usage (Figure 6). The lowest average rating was for the rotary tool speed alerts. We believe this is because the alert interrupted the ongoing action (as makers attended to it), but provided no further information as to 'why' the speed was too fast or ‘what’ problems this may cause. There was no correlation between participant’s skill level and feature ratings.

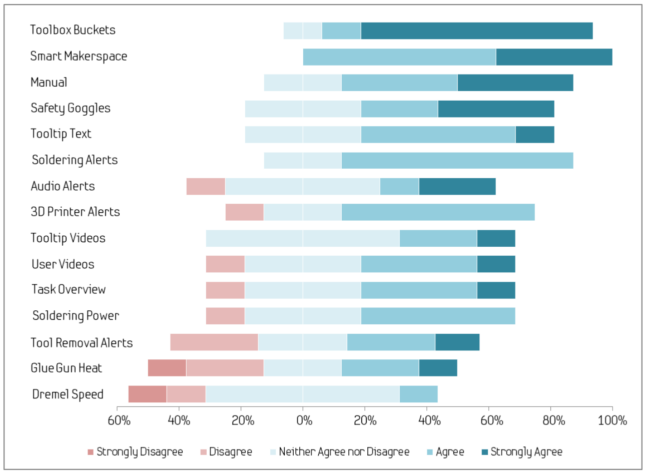

Figure 6. Chart showing Likert usefulness ratings of the Smart Makerspace features (ordered by average usefulness).

Analysis

We focus our analysis on the four issues identified in the observational study and our design goals (referenced in parentheses).

An Overview of the Task (D1)

The system displayed an overview of the task, in the form of a thumbnail of every manual page. P5 briefly examined the overview initially, exploring the steps involved in the build. P6, P7 and P8 used the overview to gauge how far through the build they were. P5 and P7 commented that it provided hints for them to explore the manual more widely, thus pre-emptively finding solutions to problems that would have later arisen. P7 was the only participant to step through the entire manual before beginning the task. Alongside the overview, the participants could also use the user videos for problem solving, without the need for a better understanding of the task as a whole.

Upon starting the task P5 said:

> *‘If I was doing this normally, my first thing would be to pick up these pieces and look at them before I looked at any tutorial, just to get a feel for what I am dealing with here.’*

It is during this initial exploration that makers formulate a sense of what a task may involve and how component features will fit together. This comment demonstrates an interest in exploring a task through physical materials and tools in additional to through the manual, in turn supporting a more natural skill-based exploration.

Domain Knowledge and Tool Usage Details

All of the participants used the additional information beyond the manual (*D2*). The participants typically began by looking at the manual, before exploring the previous user videos (the next closest information) and finally the ToolClips. Six participants used tools not called for in the manual as a direct result of the additional videos, for example using a ‘3rd hand’ device to assist with soldering. This both encouraged novice makers to learn about a new tool and prompted more experienced makers about the existence of additional tools. The more experienced participants used the ToolClips to clarify details of tools they were not familiar with, such as the preparation of the rotary tool. The less experienced participants used both the additional user videos and the ToolClip information (*D3*).

All participants commented on the audio alerts in the system. Upon hearing the positive audio tone as a result of correctly initializing the 3D printing, P2 said: *‘Did it know I just did that? That’s cool!’* Similarly, 6/8 participants responded quickly to the alert tones concerning the power tool usage, with 5 heeding the rotary tool speed warnings and 6 stopping to look for safety goggles (*D3*).

Tool Selection

The toolbox lights were universally liked by the participants (*D4*). Upon noticing the lights, P5 commented: ‘*Oh that’s great.’* This was one of the most noticeable differences between the two studies. It was clear from our observations that the toolbox lights reduced the time spent looking for tools and increased confidence in correct tool selection.

DISCUSSION

We are encouraged by the positive response to our system; the perceived usefulness of our features (13/15 rated useful on average) and that both novice and expert makers alike enjoyed using our system and made use of the wider information provided.

When using the *Smart Makerspace*, our novice participants made use of tools and techniques more akin to ‘experienced makers’ (D2). In our initial observation study, novice makers struggled to maintain contact between wires when soldering. As a result of the *Tooltips* and *User Videos* in our Smart Makerspace, participants used both the 3rd hand tool (to hold wires in place) and twisting techniques for creating temporary wire joints – as you would expect to see in more experienced maker practice. Furthermore, in our original study 5 participants had to be reminded to wear safety goggles for soldering, though the instruction material specifically prompted for their use (a rarity in existing *Instructables*). In our *Smart Makerspace,* only 2 participants had to be explicitly prompted (with 1 wearing prescription glasses, affording a level of safety that the more experienced participant was comfortable with) as a result of our table’s visual and auditory prompts (D4). These more nuanced approaches to maker tasks, and demonstrations of safer practice, serve to highlight the benefits of our system.

Finally, we were keen to explore the concerns surrounding technology adoption in makerspace-style environments. As we used a large and expensive display as a workbench, we were encouraged to see participants freely adopting the surface. P4 repeatedly swept and blew the dust and off-cuts onto the wider screen (which was protected by an acrylic sheet). P5 and P7 stripped wires and prepared for soldering on the screen itself beside the protective wooden surface. So, whilst damage is still a constraint for large tabletop screen adoption today, given the increased ubiquity of screens in varied environments and the adoption of the surface we witnessed in our study, we believe that this style of screen usage is promising for the future.

The Smart Makerspace was motivated and evaluated based upon our authored maker task. This task was intentionally designed to span the common skills and tools required in making and thus included a more varied skillset than typically required for any one task. This provided a broad platform from which to motivate our work and observe a wide range of maker practice. That said, no one task can capture the full spectrum of maker intricacies, which further exploration may come to highlight. With this in mind, this work sought to highlight the wider similarities in the challenges faced by novice hardware and software users and demonstrate the suitability of software-tutorial techniques in hardware practices, such as with ToolClips [5] and tool guidance [3, 9]. Our observations demonstrate increased occurrences of 'expert' and safe practice, alongside widespread adoption and appreciation of the additional information, supporting this approach.

FURTHER SYSTEM REFINEMENTS

Based on the analysis and feedback of our Smart Makerspace study, we implemented 3 additional features.

First, as a result of the overview observations regarding exploration through materials and tools, we have since included a 'query-by-material' and 'query-by-tool' function to the beginning of a task (*D2, D4*). Thus, when a maker picks up a material piece or specific tool, the manual automatically jumps to the first step in which that piece/tool is used; highlighting other related pieces and tools and displaying related videos (*D4*). This functionality is similar to the UI and Data probes used in Chronicle [6] and begins to facilitate a less-prescriptive task ordering.

Secondly, we originally configured our system such that the ToolClips and other user's videos were displayed automatically for every stage (*D2*). Our rationale was to make the build as easy as possible for novice makers. However, some participants suggested they would prefer to choose when and if the additional supporting information would be available. Thus, we now include a mode where this additional information is only displayed if the users explicitly request it by pressing a button. In this way, makers can better challenge themselves before seeking further help. Furthermore, this information opt-in reduces the amount of structure that the Smart Makerspace adds to maker tasks – an inherently unstructured activity. Finally, while participants appreciated the safety goggle warnings, they were surprised that our tone played when a tool was removed from its base, regardless of whether they were wearing the glasses or not. To address this limitation, we created a pair of smart safety glasses (Figure 7). Using conductive tape on the nose rest and a wireless transmitter, the system can sense if the glasses are being worn, thus further increasing the relevance of any safety information.

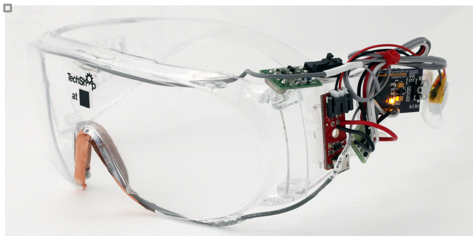

Figure 7. Custom smart safety glasses

FUTURE WORK

To enable our exploration of the *Smart Makerspace*, we manually authored the current example task. Dynamic instruction generation, however, remains an interesting and promising avenue for future work. Many of the sensing techniques that we deployed (tool sensors, toolbox highlighting, overhead camera tracking) could also be used for capture, with little or no additional augmentation. Furthermore, editing of instructional videos and automated tutorial preparation has been explored at length in the domain of software tutorials (e.g. [1, 4, 5, 13]), and we would be keen to combine these techniques with the physicality of our content delivery technique. Such efforts would build upon the DemoCut work [2] which has already tackled some of the issues with generating instructional content for physical tasks.

The Smart Makerspace has wider implications for existing makerspaces. While a fully-implemented smart space, may not be feasible, the standalone implementation of smart tools for safety alerts could provide significant benefits within group makerspaces. Not only would the alerts serve as a timely reminder for safe practice, but also alert other makers to potential dangers around them. While our smart makerspace goes some way towards reducing the need for constant supervision, we do not attempt to completely remove the need for an expert. It is hard to foresee a future where tools are so 'smart' that they can mitigate all risk without constraining freedom of use, however this remains an exciting avenue for further work.

In the future, we would like to perform a formal quantitative study of the Smart Makerspace. Our observational studies were not designed to elucidate quantitative A/B comparative results, rather to provide informed design rationale and initial feedback for our work. From here, we aim to inform and motivate future work in this area, while providing feedback on our design criteria.

CONCLUSION

We have presented a Smart Makerspace; providing a rich instructional experience for physical tasks. We conducted an initial exploration of maker tasks that highlighted 4 target areas for augmentation: an *overview of the task*, *domain knowledge, tool selection* and *tool usage details*.

We detailed the features of our Smart Makerspace, utilizing varied media types and tool-based sensing to provide additional context-relevant information. Our design drew upon lessons learned from research on software tutorials. We conducted a system study that resulted in positive user feedback, with 13 / 15 features of our Smart Makerspace considered useful. Overall, we have shown that increased connectivity through a 'smart' approach (as promised by the *Internet of Things* concept) provides exciting opportunities for immersive instructional environments for makers.

REFERENCES

1. Chi, P.-Y., Ahn, S., Ren, A., et al. MixT: Automatic Generation of Step-by-step Mixed Media Tutorials. *UIST '12*, 93–102.
2. Chi, P.-Y., Liu, J., Linder, J., et al. DemoCut: Generating Concise Instructional Videos for Physical Demonstrations. *UIST '13*, 141–150.
3. Fernquist, J., Grossman, T. and Fitzmaurice, G. Sketch-sketch Revolution: An Engaging Tutorial System for Guided Sketching and Application Learning. *UIST '11*, 373–382.
4. Grabler, F., Agrawala, M., Li, W., Dontcheva, M. and Igarashi, T. Generating Photo Manipulation Tutorials by Demonstration. *SIGGRAPH '09*, 66:1–66:9.
5. Grossman, T. and Fitzmaurice, G. ToolClips: An Investigation of Contextual Video Assistance for Functionality Understanding. *CHI '10*, 1515–1524.
6. Grossman, T., Matejka, J. and Fitzmaurice, G. Chronicle: Capture, Exploration, and Playback of Document Workflow Histories. *UIST '10*, 143–152.
7. Gurevich, P., Lanir, J., Cohen, B. and Stone, R. TeleAdvisor: A Versatile Augmented Reality Tool for Remote Assistance. *CHI '12*, 619–622.
8. Henderson, S.J. and Feiner, S.K. Augmented Reality in the Psychomotor Phase of a Procedural Task. *ISMAR '11*, 191–200.
9. Kelleher, C. and Pausch, R. Stencils-based Tutorials: Design and Evaluation. *CHI '05*, 541–550.
10. Kim, J., Seo, J. and Han, T.-D. AR Lamp: Interactions on Projection-based Augmented Reality for Interactive Learning. *IUI '14*, 353–358.
11. Kong, N., Grossman, T., Hartmann, B., Agrawala, M. and Fitzmaurice, G. Delta: A Tool for Representing and Comparing Workflows. *CHI '12*, 1027–1036.
12. Korn, O., Schmidt, A. and Hörz, T. The Potentials of In-situ-projection for Augmented Workplaces in Production: A Study with Impaired Persons. *CHI EA '13*, 979–984.
13. Lafreniere, B., Grossman, T. and Fitzmaurice, G. Community Enhanced Tutorials: Improving Tutorials with Multiple Demonstrations. *CHI '13*, 1779–1788.
14. Löchtefeld, M., Gehring, S., Jung, R. and Krüger, A. guitAR: Supporting Guitar Learning Through Mobile Projection. *CHI EA '11*, 1447–1452.
15. Makerspace Team ed. Makerspace Playbook. Makerspace.
16. Olivier, P., Xu, G., Monk, A. and Hoey, J. Ambient Kitchen: Designing Situated Services Using a High Fidelity Prototyping Environment. *PETRA '09*, 47:1–47:7.
17. Pongnumkul, S., Dontcheva, M., Li, W., et al. Pause-and-play: Automatically Linking Screencast Video Tutorials with Applications. *UIST '11*, 135–144.
18. Reiners, D., Stricker, D., Klinker, G. and Müller, S. Augmented Reality for Construction Tasks: Doorlock Assembly. 31–46.
19. Rosenthal, S., Kane, S.K., Wobbrock, J.O. and Avrahami, D. Augmenting On-screen Instructions with Micro-projected Guides: When It Works, and when It Fails. *UbiComp '10*, 203–212.
20. Rosner, D. and Bean, J. Learning from IKEA Hacking: I'M Not One to Decoupage a Tabletop and Call It a Day. *CHI '09*, 419–422.
21. Sodhi, R.S., Jones, B.R., Forsyth, D., Bailey, B.P. and Maciocci, G. BeThere: 3D Mobile Collaboration with Spatial Input. *CHI '13*, 179–188.
22. Tabard, A., Hincapié Ramos, J.D. and Bardram, J. The eLabBench in the Wild: Supporting Exploration in a Molecular Biology Lab. *CHI '12*, 3051–3060.
23. Tanenbaum, J.G., Williams, A.M., Desjardins, A. and Tanenbaum, K. Democratizing Technology: Pleasure, Utility and Expressiveness in DIY and Maker Practice. *CHI '13*, 2603–2612.
24. Tang, A., Owen, C., Biocca, F. and Mou, W. Comparative Effectiveness of Augmented Reality in Object Assembly. *CHI '03*, 73–80.
25. Tecchia, F., Alem, L. and Huang, W. 3D Helping Hands: A Gesture Based MR System for Remote Collaboration. *VRCAI '12*, 323–328.
26. Torrey, C., Churchill, E.F. and McDonald, D.W. Learning How: The Search for Craft Knowledge on the Internet. *CHI '09*, 1371–1380.
27. Torrey, C., McDonald, D.W., Schilit, B.N. and Bly, S. How-To pages: Informal systems of expertise sharing. *ECSCW 2007*. L.J. Bannon, I. Wagner, C. Gutwin, R.H.R. Harper, and K. Schmidt, eds. Springer London. 391–410.
28. Tseng, T. and Resnick, M. Product Versus Process: Representing and Appropriating DIY Projects Online. *DIS '14*, 425–428.
29. Uriu, D., Namai, M., Tokuhisa, S., et al. Panavi: Recipe Medium with a Sensors-embedded Pan for Domestic Users to Master Professional Culinary Arts. *CHI '12*, 129–138.
30. Wakkary, R., Schilling, M.L., Dalton, M., et al. Tutorial Authorship and Hybrid Designers: The Joy (and Frustration) of DIY Tutorials. *CHI '15*, 609–618.
31. Weichel, C., Alexander, J., Karnik, A. and Gellersen, H. SPATA: Spatio-Tangible Tools for Fabrication-Aware Design. *TEI '15*, 189–196.
32. Yamashita, M.M., Yamaoka, J. and Kakehi, Y. Enchanted Scissors: A Scissor Interface for Support in Cutting and Interactive Fabrication. *SIGGRAPH '13*, 33:1–33:1.
33. Zoran, A. and Paradiso, J.A. FreeD: A Freehand Digital Sculpting Tool. *CHI '13*, 2613–2616.