

# Turn-by-WiAR: A Computationally-Mediated Approach to Rapid Prototyping of Physical Objects

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Technical Report No. UCB/EECS-2019-70

<http://www2.eecs.berkeley.edu/Pubs/TechRpts/2019/EECS-2019-70.html>

May 17, 2019

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**Turn-by-WiAR: A Computationally-Mediated Approach to Rapid Prototyping  
of Physical Objects**

by

Vedant Saran

A thesis submitted in partial satisfaction of the

requirements for the degree of

Masters of Science

in

Electrical Engineering and Computer Science

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Eric Paulos, Chair

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Spring 2019

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## Abstract

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In recent years, the proliferation of low cost digital fabrication devices has greatly reduced the barrier to entry of making. However, these tools expose narrow digital interfaces which limit the ways in which users can design and prototype with them. In particular, the ‘click-to-print’ workflow of tools like 3D-printers lose many of the tangible and embodied features of physical making. In this thesis, we reimagine the way computation can mediate the digital design and prototyping of physical objects. We present Turn-by-WiAR, a novel smart tool that uses augmented reality (AR) and drive-by-wire haptics to combine the design metaphors of Computer-Aided Design (CAD) with the tacit knowledge of hands-on making. In embedding the capabilities of a manual fabrication tool with computer-generated visual, sonic, and haptic augmentations, we design a number of new interactions that promote a more embodied prototyping process. An evaluation with novice practitioners shows how our tool de-risks exploration, boosts creativity, foregrounds material properties and machine tendencies, and increases precision. Finally, we envision how such kinds of smart tools might enable non co-located real-time collaborative design, in-situ creation, and other novel fabrication workflows.

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## Acknowledgments

I would firstly like to thank Kevin Tian for his tireless work and brilliant insight on all the hard(ware) parts of this research. Many thanks to my advisor, Eric Paulos, for introducing me to the wonderful world of HCI, and showing me just how provocative and artistic computing can be. It's been a privilege to work with and learn from my undergraduate collaborator, Anna Brewer. I'd also like to thank to Cesar Torres and the other members of the Hybrid Ecologies Lab for their guidance and support, and for creating such a vibrant, welcoming environment. Finally, I'm incredibly grateful for my parents and little brother, who've always been supportive and encouraging of me and my research. Thank you.

# Chapter 1

## Introduction

### 1.1 Motivation

Physical prototypes are an incredibly important part of the fabrication process, serving as a starting point for innovation, improvement and experimentation [28]. As the proliferation of the Maker movement <sup>1</sup> and access to digital fabrication tools continues to increase, the number of practitioners engaging in fabrication – and by extension prototyping – has increased tremendously. However, the new digital fabrication tools whose proliferation spawned the Maker movement aren’t equally adept at supporting explorative design. The most effective prototyping tools can structurally boost in-situ creativity and encourage exploration of the entire design space, leading to better built objects. But the same “click-to-make” model that makes 3D printers and the like so popular also narrows the way we can interact with them, skewing a process as hands-on as *making* towards heavily computer-oriented workflows. That’s not to say that digitally driven design tools don’t bring anything of value: They guarantee extreme precision for complex geometries, have generally shallow learning curves, and can enforce structured workflows for novice users. This tension between the affordances of digital interfaces and the embodiment of physical ones is one of many that make designing effective prototyping tools difficult. An effective prototyping workflow additionally must fight the following tensions:

- Allow the ability to iterate through designs more rapidly than real fabrication processes, but also prove manufacturability and explain how machine-specific parameters might affect the final built object.
- Be simpler in construction than the final object, but lend understanding of material properties, and how it might interact with users, other objects, and the environment.
- Leverage the embodied knowledge and directedness of craft, while still allowing for exactness.

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<sup>1</sup>[https://en.wikipedia.org/wiki/Maker\\_culture](https://en.wikipedia.org/wiki/Maker_culture)

In this thesis, we propose a way to resolve – or at least reduce – these tensions through an *augmented* tool. By combining visual, auditory and haptic cues in both familiar and unfamiliar configurations, we design a new prototyping process that combines the directness of physical tools with the flexibility of CAD. We instantiate these ideas through a lathe, augmented by haptics and AR.

## 1.2 Why lathes?

A lathe is a subtractive fabrication tool in which the material being formed is continuously in rotation, and tools move about the spinning material to cut or deform it to the desired shape. Lathes are historically as well as practically significant and often referred to as mother tools. They have endured because of their unique ability to create cylindrical geometries.

Lathes are found in diverse contexts, exhibiting varying levels of handedness in how the tool is used, as shown in Figure 1.1. In the case of a ceramicist’s pottery wheel, hands are directly used *as* tools. One step removed from this directness is a wood lathe, where sharp tools are mounted on handles, giving the craftsperson greater leverage over the cutting forces and process. Going one step further is a manual lathe, where cutting tools are mounted to a two-axis gantry, and the tools are moved through the use of handwheels — large rotary knobs which transmit the rotational motion supplied by the user to linear motion of the two axes through a mechanical transmission. In this third style of lathe, the physical transmission mechanism between the user and the gantry acts as a rudimentary mediator between the actions of the user and the actions of the lathe. This decoupling between user action and machine action augments the capabilities of the user through greater safety, increased productivity, and improved accuracy. It also reduces the directness of how the user works with the material, but the tactile sensations of working with the material are not entirely lost, as forces felt by the cutting tool are transmitted through the gear ratio of the rotary to linear transmission. As lathes are subtractive tools, these kinds of lathes often have a chipguard: a transparent shield that allows visibility of the operation while protecting the operator from debris, such as flying wood chips or sprays of machining fluid. The furthest removed from directness is the Computer Numeric Control (CNC) lathe. In the CNC case, this decoupling is taken to an extreme, where all actions performed by the machine must be specified through a series of software packages.

## 1.3 Why AR?

Augmented reality (AR) is the set of technologies that enables digital information to be superimposed on top of a user’s view of the real world. It is not a new technology; Ivan Sutherland developed the first head-mounted display system in 1968. The principle of stereoscopy, the fundamental principle on which most modern AR and VR headsets are based on, has been employed in 3D viewers since at least the early 19th century. However, like digital



Figure 1.1: Different kinds of lathes. From top-left clockwise: A ceramicist's pottery wheel, a wood lathe, a manual lathe, a CNC lathe [9], [21], [50], [20].

fabrication, AR has seen a recent explosion in interest as the technology has become better, cheaper and more accessible. Pokemon Go, a mobile AR app released in 2016, took the world by storm, drawing in over 150 million active users and earning several billion dollars in revenue. The app demonstrated that smartphones — already equipped with cameras, sensors, networking capabilities and powerful mobile processors — were a prime modality through which AR content could be distributed. Since then, a number of popular mobile applications including Snapchat, Facebook, and Apple's Measure have integrated AR features to great commercial success.

Augmented reality is most effective when it realistically composites the virtual with the real. This makes it a natural fit for digital fabrication, which also aims to bridge the gap between digital CAD representations of objects, and physical objects themselves. By linking a physical object to a digital design, we can shorten iteration cycles and offload expertise to computer algorithms [44]. AR allows us to leverage all the benefits of digital representation, design, and testing. At the same time, it also uses sensing to understand the physical world, and its interaction with digital content, making it a viable direction for modern digital fabrication processes.

We believe that as virtual and augmented reality technologies become more mainstream,

interface design tools will need to update to support the immersive capabilities of these new device classes. We believe that designing these new immersive interfaces will be difficult — far more so than creating prototypes of graphical user interfaces — because they must be seamlessly integrated with the real world, and engage a much greater number of human senses than 2-dimensional GUIs. The physical making community, with its innate focus on embodied interactions and tacit knowledge transfer, understands how to achieve these things well. Therefore, although we do not directly study the latter in this thesis, we hope that this work starts a conversation around using AR for digital fabrication, but simultaneously, around using physical making processes as metaphors in AR interface design.

## 1.4 Turn-by-WiAR

We introduce Turn-by-WiAR as a jointly physical-digital system for prototyping the kinds of geometries fabricated on a lathe. We do this by identifying and augmenting two sites on the lathe amenable to this kind of hybrid control.

First, we replace the transparent display of a traditional chipguard with an AR enabled tablet(which we nickname *chipguARd*). This allows the system to digitally mediate the output of the system, computationally altering the user’s perception of the operation. For example, we can change the perceived material the user is cutting from wood to plastic to metal instantaneously at the click of a button, by tracking the position of the physical workpiece and superimposing a digitally rendered layer on top of it in the camera feed.

Secondly, we replace the mechanical transmission of a manual lathe’s handwheels with a computationally-mediated electromechanical system, to directly and digitally couple the user to the tool. Since the user’s input to the machine is performed through handwheels that control the lathe in a drive-by-wire<sup>2</sup> configuration, we allow couplings that are not restricted by any mechanical configuration. For example, the movement applied to the input wheels can be scaled down when calculating the cutting forces, to guide a user through performing a delicate cut.

In general, the act of working with a lathe is referred to as ‘turning’. We reference this in our title both as a reference to the tool we are working with, as well as to highlight the embodied, tangible interface through which the user can create prototypes. Along with the ‘by-wiAR’ system (a portmanteau of by-wire and AR), the system computationally modulates the user’s visual, auditory, and haptic experience of using the machine, altering the user’s sensory perception to foreground physical machine properties and materiality when relevant, and utilize digital affordances otherwise.

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<sup>2</sup>[https://en.wikipedia.org/wiki/Drive\\_by\\_wire](https://en.wikipedia.org/wiki/Drive_by_wire)

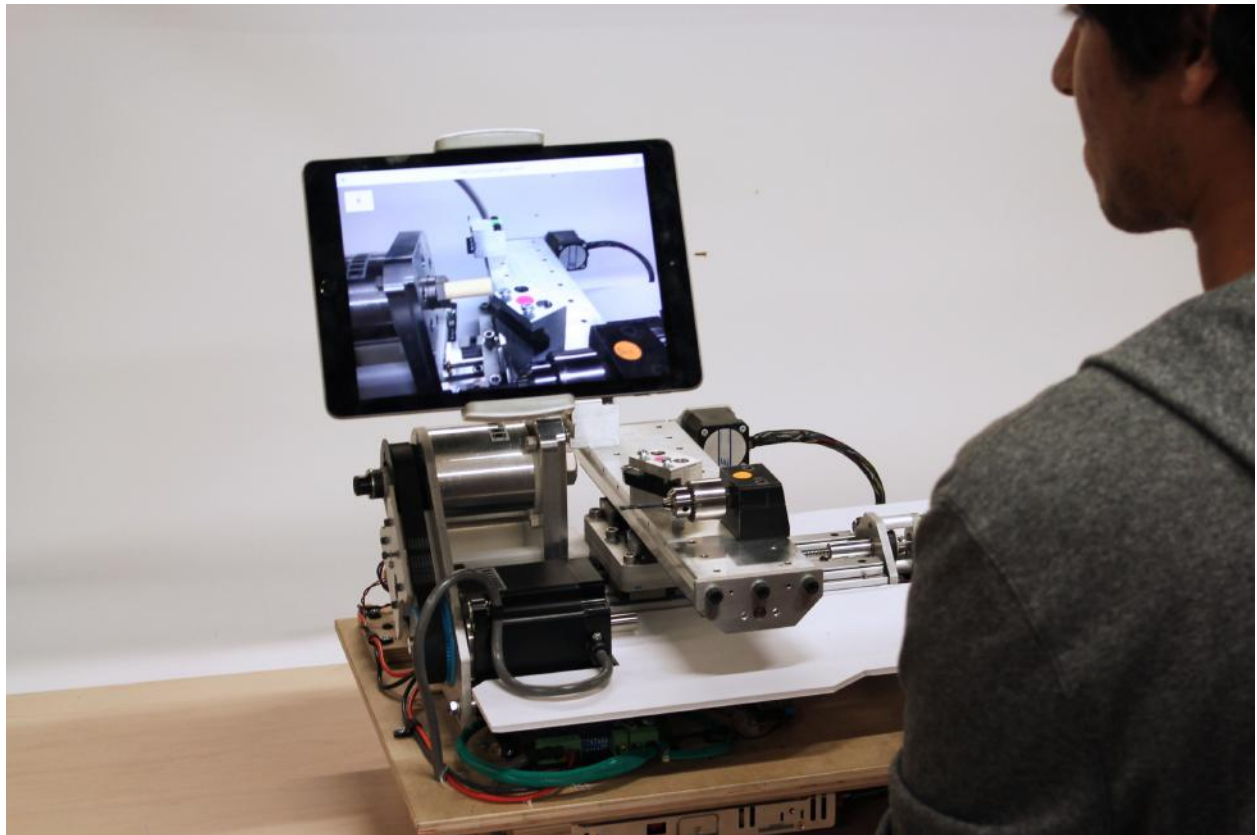


Figure 1.2: A user turns a virtual stock on the Turn-by-WiAR system. The cylindrical wooden stock visible in the center of the screen is not made of real material, but a virtually rendered one superimposed on top of the machine using AR. In this orientation, the camera is on the bottom right of the tablet, allowing the screen to display at eye-level what is visible around the collet of the lathe.

# Chapter 2

## Related Works

This project is inspired and informed by related work in augmented reality enabled hand-held tools, interactive fabrication, haptics, as well as critical perspectives for digital fabrication.

### 2.1 Augmented Hand-Held Tools

Contexts as diverse as sculpting [62, 42], spray-painting [46], on body fabrication [14], and wood routing [43] have been explored, as well as many more in both industry and academia, as surveyed by Zoran et al. [63]. Schoop et al. explored augmenting hand tools with sensors and projector-based AR in the context of an *ecosystem* of smart connected tools — drills, miter saws, etc — for dynamic tutorials [45]. However, the premise of many of these projects is that the user is anchored to a pre-existing digital model that guides the operations they perform.

As an alternative to this view, many projects augment tools with the purpose of assisting in the real-time creation of digital models. *Enchanted Scissors* [61] implemented a pair of scissors which respond to conductive ink drawn by the user, to either allow or disallow cuts via force feedback on the handles of the scissors. Yamaoka et al. [60] developed a drawing system for physically guiding a ballpoint pen using a gantry mounted magnet, and explored interactions spanning manual and computer guided drawing. *Protopiper* allows users to quickly build large sketch models using a hand-held tape extruder [2].

These interpretations of augmented hand held tools advocate for open ended fabrication workflows. We don't limit our definition of augmented hand tools just to those that integrate visual AR into their tools. Rather we use the more holistic definition for augmented reality that includes all computational modifications that leverage information about the real world to inform digital design, or vice-versa. This could be see-through, pass-through, projective, or autostereoscopic.

Working in this vein, our project aims to combine sensory inputs to build an augmented tool that is untethered to a preconceived CAD model, fully supports open ended exploration, and is capable of augmenting a user's personal making capabilities.



## 2.2 Interactive Fabrication

While not hand-held, the following fabrication machines share the similar goal of enabling more direct interactions between users and fabrication tools. Willis et al. explored how embodied input such as physical movement or voice can be interpreted as geometries for fabrication [58, 59]. In the context of interacting with a laser cutter, Mueller et al. implemented a digital 'drafting table' on the lid of a laser cutter to create assemblies [32] and folded objects [31]. More directly interacting with a CNC machine has been explored in the context of woodworking [49] and in large scale drawing [26]. These projects focused on more direct methods of communicating design intent to a fabrication tool for fabrication, but these fabrication tools can just as importantly function in the reverse: to inform the user about the state of their physical work, or the capabilities of the machine system.

In our work, we leverage haptics and AR in both of these directions, allowing them to engage with material and machine more fully.

## 2.3 Interactive Design: Digital/Physical Correspondence

While the benefits of Computer Aided Design (CAD) are clear – communicating designs between humans and machines, digital manipulation of designs, managing complex models – there remain many limitations of GUI interfaces for physical design tasks. Many researchers have addressed this challenge by utilizing embodied and tangible interfaces for better representing physical objects with digital proxies.

Using real world objects as input for a CAD model has been explored in systems such as CopyCad [13] and MixFab [56]. Both systems leverage augmented reality to digitally interact with physical objects. Physical to digital correspondence in measurements was explored with smart measuring tape [24], and a bidirectional correspondence was explored with actuatable calipers [57]. Researchers have also used pen interfaces with paper models as input for a CAD model [47].

Interactive construction kits capable of sensing their shape have also been used as input for CAD [25, 3]. Reform and Patching Physical Objects developed technical pipelines for bi-directional fabrication, where after a physical model leaves a fabrication tool, the geometries can still be modified by the machine [48], or by both user and machine [48]. Systems have also been created to investigate concurrent physical fabrication of a low fidelity model [33] in parallel with the user's creation of a CAD model [38, 37]. RoMA uses passthrough AR to providing a precise in-situ modelling environment in which the user guides a robot arm with a material extruder attachment (see Figure 2.1.) Other projects tried to lower the barrier to entry for CAD through physical fabrication of a proxy as input [36]. As AR and VR mature as commercial technologies, a number of design tools are becoming available. Tiltbrush[16], Medium [54] and Quill [55] use VR for stroke-based 3D sketching, voxel-based sculpting,

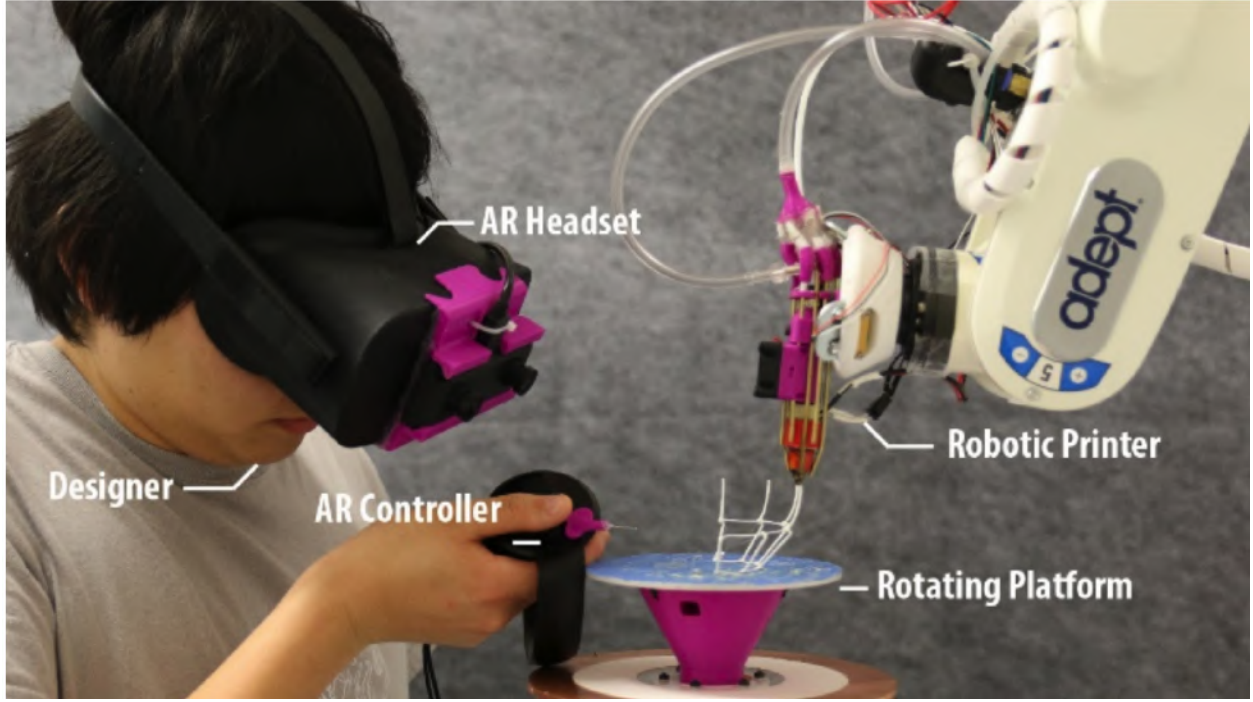


Figure 2.1: RoMA uses pass-through AR to providing a precise in-situ modelling environment in which the user guides a robot arm with a material extruder attachment.

and 3D animation respectively. However, none of these tools provide physical feedback, and their design platforms remain disjointed from the fabrication process.

Our proposed system attempts to lower the barrier even further by allowing the prototypes to live as fully digital objects with no physical correspondence. At the same time, through haptics and AR, we can embed these digital objects with many of the properties that make physical prototypes so desirable.

## 2.4 Haptics for Digital Fabrication and AR/VR

A variety of haptic modalities have been explored by researchers in contexts such as driving, surgery, and AR/VR. Here, we briefly highlight a few pieces of related work to give a sense of the breadth of the different haptic modalities available. Ungrounded force feedback has been explored through flywheels [5], and asymmetric acceleration of voice coil actuators [8]. A combination of force feedback and skin stretch has been explored in [40] for steering wheels. Variable stiffness haptic controllers were developed using software defined springs in [17]. A system for rendering normal and textured surfaces was proposed in [6].

Within digital fabrication and adjacent domains, haptics has been utilized only a few ways. Haptic intellegentsia [18] allowed users to ‘feel’ an existing 3D CAD model by using

a hot glue gun attached to a haptic controller. In [60] a magnetic attraction force was used to control the movement of a pen for drawing. Haptics has also been used too augment input in computer aided design [39]. Though not strictly ‘fabrication’, skin deformation haptics have been suggested as a way to mediate teleoperated surgery [41]. Many of these projects embody a very literal view of the types of forces — and more broadly the types of representations of reality - that can be output.

Haptics have also extensively been integrated with AR/VR systems. Various researchers have explored using drones [23], [1], [19], robotic arms [37], heat delivery [35], ultrasound [30], and passive proxy objects [4] to induce haptic responses in AR/VR systems to make them feel more immersive. While haptics were not utilized as output, the force information of a pre-planned CNC lathe toolpath was communicated to the operator in [34] using a spatial AR display.

Our contribution to this space is to leverage the inherently artificial nature of haptics not only to render realistic kinesthetic forces on virtual objects, but also to reimagine different types of forces that can be displayed to a user in an open ended fabrication task.

## 2.5 Alternative and Critical Perspectives for Fabrication

Researchers, artists, and designers alike have reinterpreted the role of fabrication tools to give rise to alternate forms of creative expression. Rather than using digital fabrication as a means to delegate fabrication to a machine, Torres et al. used 3-D printers to create proxies, intermediaries that guide the hands on fabrication of the final artifact in the context of wire wrap jewelry [51]. Artists and designers such as *LIA* and *Emerging Objects* have embraced the non-deterministic behavior of extruded materials to produce new aesthetics in plastic [27] and clay [15]. Devendorf et al., engaging digital fabrication through the lens of performance art, proposed a series of projects questioning the delegative relationship that pervade the use of digital fabrication tools, and has explored how materials, environments, and situated actions can similarly influence the outcome of fabrication processes [11, 12]. In [22], musical composition metaphors informed new interactions which allow a user to continuously edit an object being fabricated by a 3D printer.

On the AR side, art installations *LiAR* [29] and *Fight!* [7] show how AR and VR can be used to subvert expectations and make people feel intentionally uncomfortable by distorting their preconceived expectations of reality, virtual or otherwise.

In this project, we consider how rapid prototyping can fundamentally be an embodied activity in which our physical skills are foregrounded, and further augmented, visually, as well and sonically and haptically. We hope that this idea can act as another lens through which we conceptualize digital fabrication and prototyping.

# Chapter 3

## Interactions

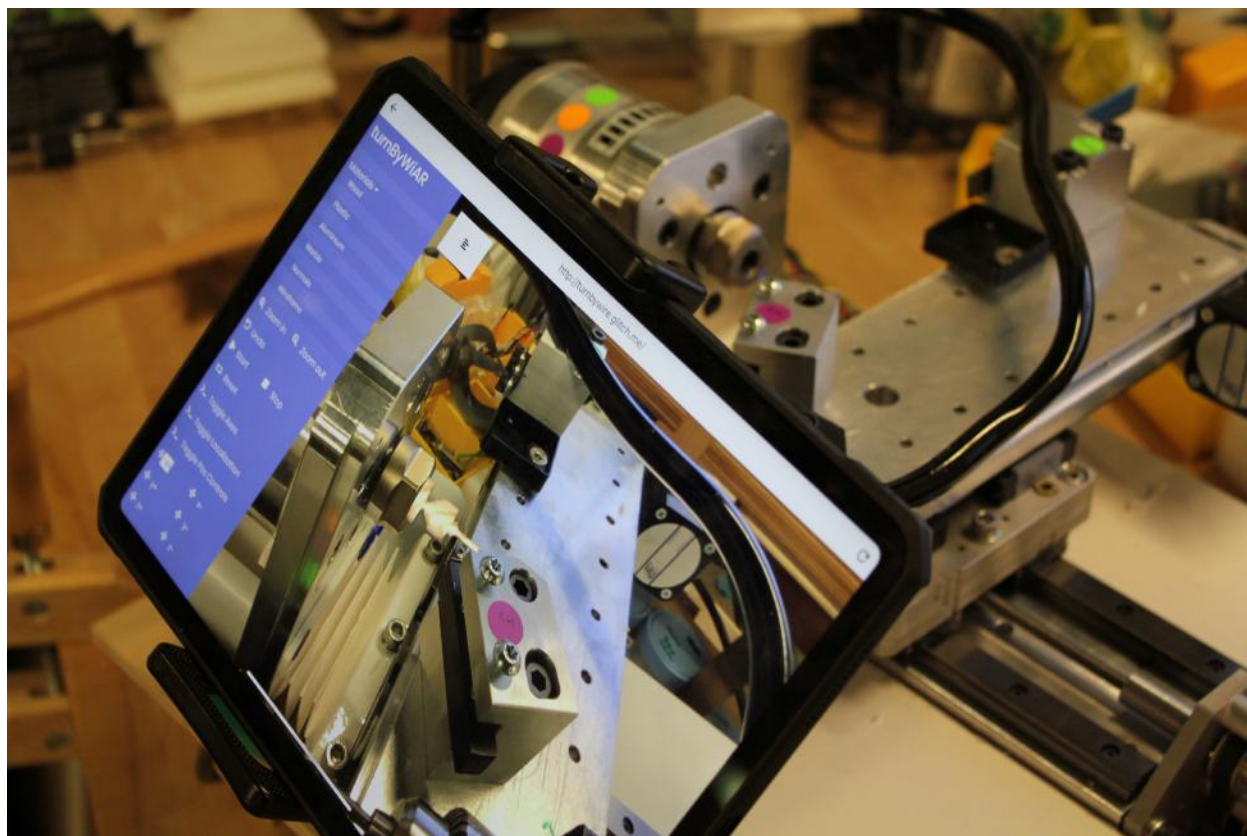
Our system leverages the direct but modulated control of digital fabrication tools via augmented reality for three primary goals: (A) representing the state of the environment, (B) extending the abilities of the environment, and (C) merging physically separate environments. We satisfy these three goals by targeting each of the main senses through which the user engages with the fabrication process: vision, hearing, and touch.

### 3.1 Representing Reality

Our system creates a digital environment that simulates the visual, auditory and haptic cues received by a user as they use a lathe. Through chipguARd, the user sees a virtual work piece, superimposed on the headstock of the physical lathe. They can see the physical cutting tools through the passthrough camera feed, and can use the handwheels to move them. As the physical tools intersect with the virtual work piece, the work piece is cut accordingly, its geometry updating in real-time to reflect the operation. This effectively blends the digital model and the physical machine together, leveraging the embodied interactions of working with the physical lathe and its tangible handwheel interfaces, while generating an editable digital 3D model. We take care to ensure that the digital material represents reality accurately as possible, by looking, sounding, and feeling as close to real material as possible. Following the master-apprentice model, we recognize the importance of training the senses to perceive materiality and the present state of materials, especially for novice practitioners [52]. Below, we explain in detail how we achieve this:

#### Virtual material

Because the work piece is entirely digital, its visual properties can be modified on-the-fly. The user can change the material between softwood, acetal plastic, and aluminum, and custom vertex and fragment shaders visually render the visual properties of each one. Along with color, texture, wood grain, etc. we additionally render the oxide layers on aluminum, show



cuttings, chips and shavings spiraling out, and simulate light reflectance and transmittance properties of each material. A prototype widget cut in wood, aluminum, acetal and marble are shown in Figure 3.2.

Similarly, the audio profile of the machine can also be realistically represented digitally. A sound recording of the headstock spinning is played when the virtual piece spins, and each virtual material emits a different sound when cut. This bridges the gap between the virtual design space and the physical fabrication space, so that when a user wants to use the machine to physically fabricate, they have expectations about the sounds itll make and therefore will feel more confident using it. Additionally, while turning, audio cues play an important role in informing the user about the quality of the cut. Grinding, clicking and cracking sounds indicate potential failures, and the pitch and volume cue the fabricator to the speed and depth of the cut. While our prototype cannot simulate the sounds of all possible failures, we do vary the pitch and volume of the cut, proportionally to cutting speed and cutting depth.



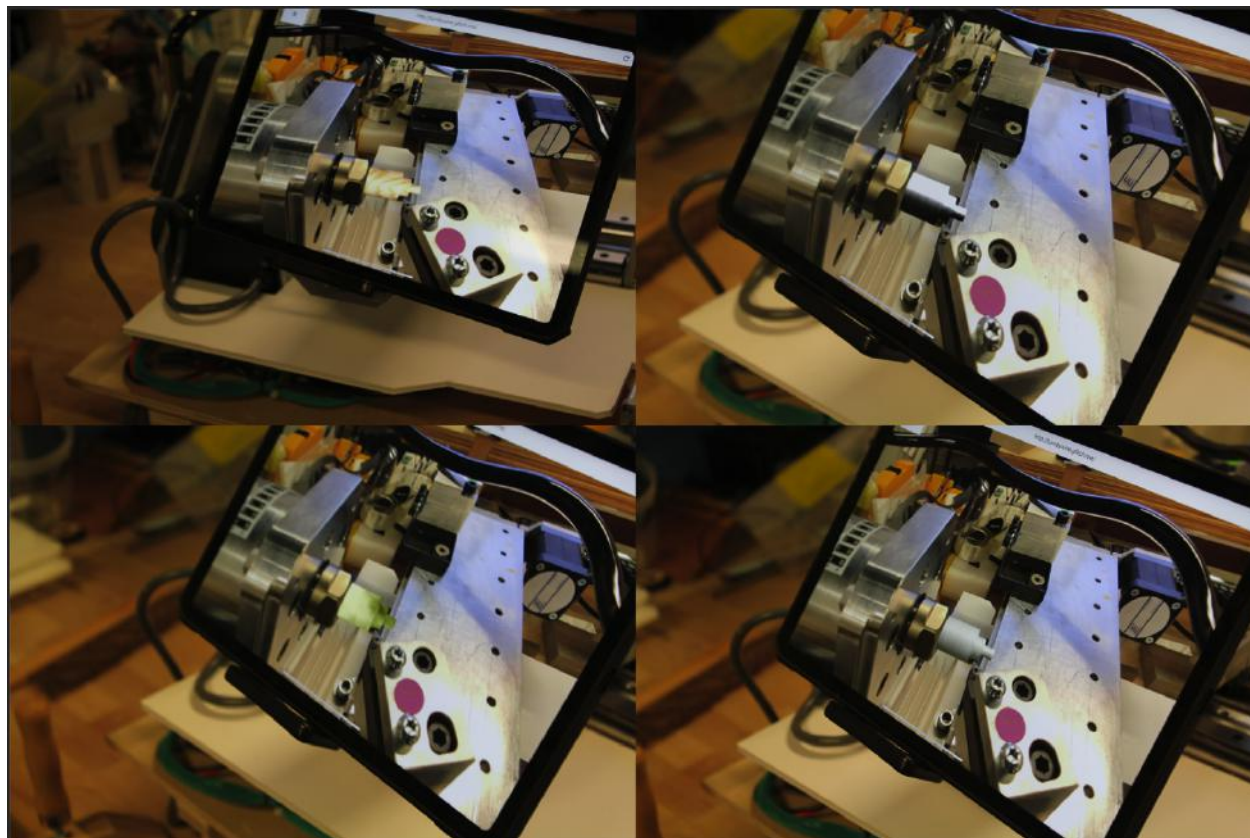


Figure 3.2: The same widget geometry rendered in different materials. Clockwise from top-left: wood, aluminum, marble, and acetal plastic.

This allows beginning users to begin to understand the various advanced sensory cues that masters use while turning, in a de-risked environment.

We use ambisonic sounds, rendered spatially as a function of the position of the chip-guARd relative to the workpiece. If the user wears headphones the audio can be rendered in 3D. As they move the device around the work piece to view it from different angles, they can hear the audio change realistically.

### Virtual cutting forces

In addition, the force of the cut is felt though the handwheel by electronically braking their motors when the virtual material is being cut. For each virtual material we set a predefined haptic profile, so that users can feel the haptic sensation of cutting that particular material. This allows the user to experience what cutting a particular material might *feel* like, despite the fact that the cutting tool is moving through empty air. This makes the act of designing more tangible, and reminds the user to consider material-specific properties

during the design-stage itself. Additionally, it trains the user to recognize and respond to these cues when they cut real material.

## 3.2 Extending Reality

Although we strive to represent reality as accurately as possible, we also acknowledge that the digital realm provides many functionalities with no real-world equivalent. For example, CAD packages allow arbitrarily high accuracy and precision with an ease impossible to achieve with hand tools. Additionally, CAD and myriad other software tools exploit the re-usable nature of bits (versus atoms) to minimize risk, encourage exploration, and create non-linear workflows. Finally, computer intelligence can simplify complex manual manoeuvres and automate tedious processes.

Augmented reality, by virtue of its ability to blend together the real and the virtual, allows us to leverage many of the benefits of real-world fabrication (such as tacit knowledge and material understanding) while using many of these digital features. These interactions when designed carefully bring the best of software capabilities to the physical prototyping workflow.

In this project, we do this by (1) bringing metaphors like undo/redo and copy/paste from the realm of desktop CAD packages into the real world, and (2) by creating new digital metaphors native to the context of hybrid digital/physical fabrication, such as remappings. We detail them all below.

### Undo/Redo

Undo and redo are commonly employed metaphors in digital content creation and are seen in applications as diverse as word processing, image editing, and spreadsheets. They are used heavily by novice and expert users alike to reverse actions due to mistakes, or change in user intention.

In this work, we imagine what a version of this concept might look like in a physical making context where we cannot lean on the traditional discretization of operations for undo and redo. In digital contexts, inputs are discrete user-initiated events which makes it straightforward to define units of operation for undoing and redoing. On a lathe, with the exception of a few operations (parting off, and perhaps end chamfering), most operations are continuous processes that lack clear semantics of a “start” and an “end”. For example, a single pass of a facing cut can imprint many different shapes along the length of the work piece. This makes a discrete operation-based undo hard to define. Therefore, we introduce a *temporal* undo, allowing the user to revert the state of operation to a previous point in time. This could be either an absolute marker (a timestamp) or a relative time (offset from the current time.) By default our undo and redo operations are in intervals of 1 second, but we allow for precision up to 0.033 seconds (30 Hz), and store past history for infinitely long.

We imagine this to be a particularly compelling feature because the ability to undo and redo removes the stigma around making mistakes. Traditional lathes, by nature of being a purely subtractive tool, are particularly unforgiving, especially to novice users. If too much material is removed by accident it cannot be added back; the piece must be discarded and work started anew. Not only is this discouraging to beginners, but it introduces material resource constraints that limit the number of iterations a user can perform. Both of these facts combine to make machinists risk-averse and thus less creative for fear of making time-prohibitive and material-prohibitive mistakes.

Adding the ability to undo and redo operations on the (virtual) material de-risks turning, freeing users from the sometimes debilitating risk of failure. This allows users to design more freely and creatively, and thus engage more deeply with the design task at hand. For novice users, it additionally allows them to practice cuts over and over again. Over time, this allows them to get more familiar with the operation of the machine and build confidence.

## Snap-to-guide

Snap-to-guide is a feature used in many graphics design and image manipulation softwares to guarantee alignment and exact dimensions. In our system, we use a combination of visual feedback and haptics to inform the user of these.

Guides (detents) are added and visualized at user-specified locations in augmented reality, as shown in Figure 3.3. When the cutting tool approaches the guides, the “snap” is felt in the handwheels. The inclusion of haptics here affords a subtle mechanism for the user to track their current location in space, and, in the spirit of embodied cognition, offloads some of the cognitive load of spatial awareness to the body. These guides can also be used with real material in the lathe. In this configuration, chipguARd acts as a traditional AR display, rendering the guide-line as an information overlay over the real material.

## Virtual grid

While the virtual guides are placed at user-defined locations, the virtual grid marks divisions at equal intervals along the z-axis. These form a secondary marker (after the guides) to inform the user of dimensionality and form. A demonstration of what this grid looks like is shown in Figure 3.3. Like the guides, this grid can also be useful when real material is loaded in the lathe.

## Remapped tools

By using a digital rather than mechanical coupling between handwheel and lathe, we can adjust the ‘transmission ratio’ between the handwheel’s rotation and the lathe’s motion in software. Rather than having the z-axis handwheel move the lathe only along the z-axis, this handwheel can be remapped to cut along a taper or radius, as opposed to coordinating two handwheels manually or by using a context specific jig. We conceptualize this remapping as



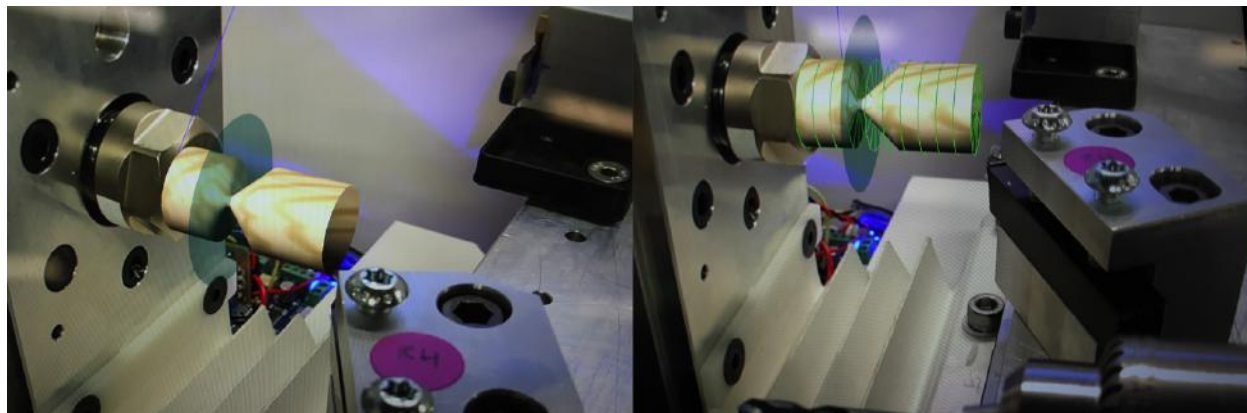


Figure 3.3: Left: A virtual guide placed 34 millimeters from the origin along the z-axis. When the cutting tool approaches the disk, it is ‘snapped’ to the precise location. Right: A virtual grid marks the work piece in 10 equally spaced divisions 10 millimeters apart.

‘virtual tools’. The dimensionality of the task is effectively reduced to highlight the most salient aspects about the design.

## Remapped audio

Alongside creating realistic sound effects that mimic those made by a lathe, we also explore integrating audio that has no grounding in the physical fabrication process. For example, instead of modulating the pitch and volume of a clip of wood turning, we apply the same transformations directly to a sine wave. This allows the user to directly perceive the physical phenomena responsible for those audio transformations (namely, speed and depth of cut), without the distractions of the other sound-emitting processes. We believe this can directly train their ear to recognize these patterns, such that they can later pick up on the same cues even on real material sounds. Additionally, we explore using virtual audio for *play*. We use the sound of bubble wrap to create popping sounds that are emitted at equal distances along the z and x axes. This cues the user in to the distance they have travelled along each of the axes. While they would not expect to hear these non-diegetic sounds in real operation, the prior association with frivolity and carefreeness that bubble wrap carries evokes a sense of play that is critical to creative engagement and effective prototyping.

## Speech interface

In addition to using audio as an output modality, we also utilize audio as input. Using speech recognizing, chipguARd acts as a digital companion that the user can talk to using natural language. We construct the recognition engine for this natural language parser from commonly used language patterns within the machinist community. Some available voice commands are:

- Start spindle rotation
- Stop spindle rotation
- Change material to  $\langle \text{wood/plastic/metal/marble} \rangle$
- Change radius to  $\langle \rangle$  mm
- Change length to  $\langle \rangle$  mm
- Undo (by  $\langle \rangle$  seconds)
- Redo (by  $\langle \rangle$  seconds)
- Reset
- Change cutting force on  $\langle x/z \rangle$  axis to  $\langle \rangle\%$
- Add guide on  $\langle x/z \rangle$  axis at  $\langle \rangle$  mm
- Turn on grid
- Turn off grid

We use some simple rule-based NLP to adjust for misheard words, synonyms, different grammatical constructions, different measurement units (millimeters vs centimeters vs inches) etc.

## Remapped cutting forces

The haptic forces experienced during cutting can be amplified or attenuated depending on the task at hand. For example, a user might choose to amplify the force on a delicate cutting tool to give themselves a more nuanced feel of how the cut is progressing. Rather than having the first indication of a broken or failing part be the failed part itself, a user of this system immediately feels that something might be awry. Additionally, it can be used as a tool to scaffold learning. Amplifying subtle cues can train the user to recognize and respond to them better they cut real material.

## 3.3 Merging Realities

Physical prototypes are useful because they have material properties and constraints that define how they can interact with the world around them. Parts fabricated on a lathe are meant to be used out in the world, and prototyping provides a time and cost effective way to guarantee that the designed part will work for its intended purpose. Augmented reality is a natural choice to enable this kind of checking and testing, since it allows for digital prototypes to interact with real-world objects and environments.

The features listed under the ‘representing’ and ‘extending’ reality sections combine to make up the fabricator view, which informs the user as they work at the lathe. The *collaborator view* enables a collaborator at a remote location to guide the machinist in the fabrication view to manufacture a part that meets real-world criteria. The remote collaborator can see the digital prototype update as the fabricator cuts it, and check for scale, fit, aesthetics, etc. remotely. She can indicate through voice or through 3D annotations dimensions, fixes, and optimizations that the fabricator should include in the prototype. The same technical infrastructure underlying this collaborator view also works in a single-user workflow: The fabricator can first design a part on the Turn-by-WiAR lathe, then inspect and test the part post-fabrication against a set of real-world criteria.

We call this “merging realities” because it allows two collaborators in different physical environments (at the lathe and at the place of usage) to co-design a part using the best abilities of both of their environments: the fabricator uses the lathe machine to guarantee manufacturability and enjoy tactile fabrication, while the remote collaborator leverages the geometry of their environment to guarantee fit and correctness. Unique to the collaborator view are the following interactions:

### Inspection

Tapping on the screen of the AR display snaps the work piece to directly in front of the user. Until the tap is released, the work piece will follow the change in translation and rotation of the device. This allows the user to move it around, and place it in specific locations in the physical environment. For more fine-grained placement, the translation buttons can be expanded from the sidebar and used to move the object at smaller, more precise increments along each of the three axes.

### Zoom-in/out

Additionally, the zoom-in and zoom-out buttons on the sidebar menu increase and decrease the size of the work piece respectively. This can be useful to closely inspect finer details in the part, or to precisely check dimensions, fit, and interaction with joinery and other parts. Similarly, the virtual materials can be changed to study the aesthetics of the prototype, and its visual cohesion (or lack thereof) with its surroundings.

### Communication

We provide several markup tools to allow the remote collaborator to communicate with the fabrication. Apart from voice chat, they can also free-form draw in 3D space, using their iPad as a controller in the vein of Tiltbrush<sup>1</sup>. The machinist using the fabricator view does not see any of the remote environment, so this is the only way to alert the machinist to the structure of the remote environment.

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<sup>1</sup><https://www.tiltbrush.com/>

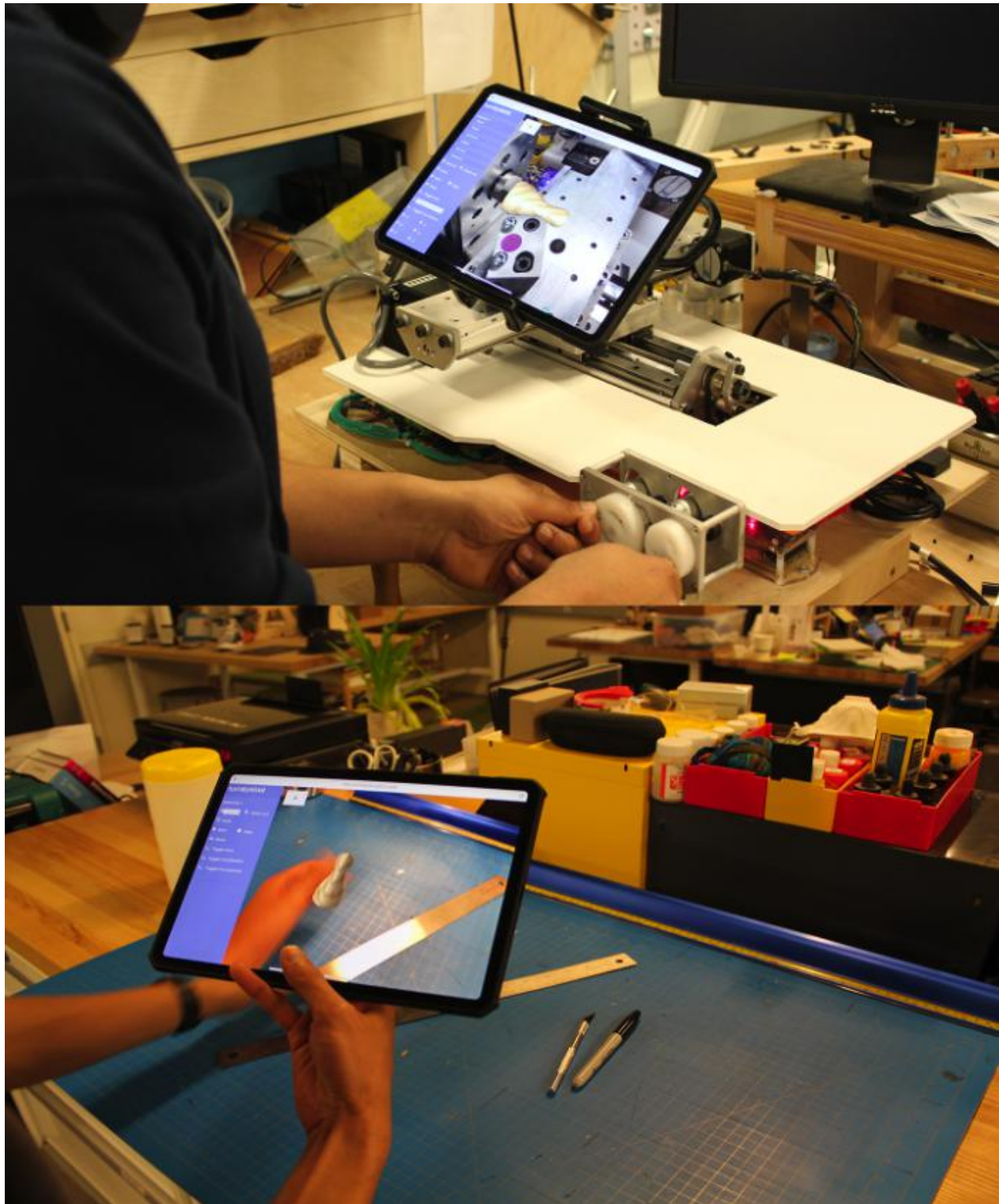


Figure 3.4: Two users collaborating to design a bowling pin. Top: Using the fabricator view, this user designs in-situ at the lathe, checking that the designed part is manufacturable. Bottom: Using the collaborator view, this user visualizes the part in the real world, checking for relative scale against other objects.

# Chapter 4

## Implementation

### 4.1 Hardware Implementation

#### Lathe

We designed and fabricated a custom desktop lathe for our system. The lathes structure is constructed primarily from 6061 Aluminum, using a combination of CNC machining, hand machining, and abrasive waterjet cutting. For ease of integration and assembly, we use linear profile rails to support the motion of the gantry. The X-axis of the machine has a maximum travel of 225mm ( $\sim 9$  inches), the z-axis of the lathe has a maximum travel of 100mm ( $\sim 4$  inches), and stock material of up to 50mm ( $\sim 2$  inches) in diameter can be cut. A schematic view of the lathe can be seen in Figure 4.1. The long X-axis of the lathe allows us to simultaneously mount multiple cutting tools in a ‘gang tooling’ configuration. Because the machine is CNC controlled, the user can easily index between these various tools, effectively using the X-axis of the gantry as an automatic tool changer. The following tools are currently mounted to our machine: a drill (used to create holes), a standard cutting tool (used to cut profiles on the outer diameter), and a parting tool (used for cutting grooves and removing the component from the stock) as visible in Figure 4.1). These tools encompass many of the common operations possible on a lathe.

Although most of our proposed interactions occur on the virtual layer, we build the lathe to be fully capable of cutting physical material as well. The spindle, which holds the component being fabricated, is driven by a NEMA 34 stepper motor. Though the maximum rotational speed is limited by the use of a stepper motor, respectable torques (approximately 4N-m at 100RPM) are achieved at lower speeds. The lathes is controlled by a microcontroller running GRBL, an open source motion control firmware. Gcode and other low level commands can be streamed to this microcontroller over UART Serial. Example geometries cut with this lathe are shown in Figure 4.2.



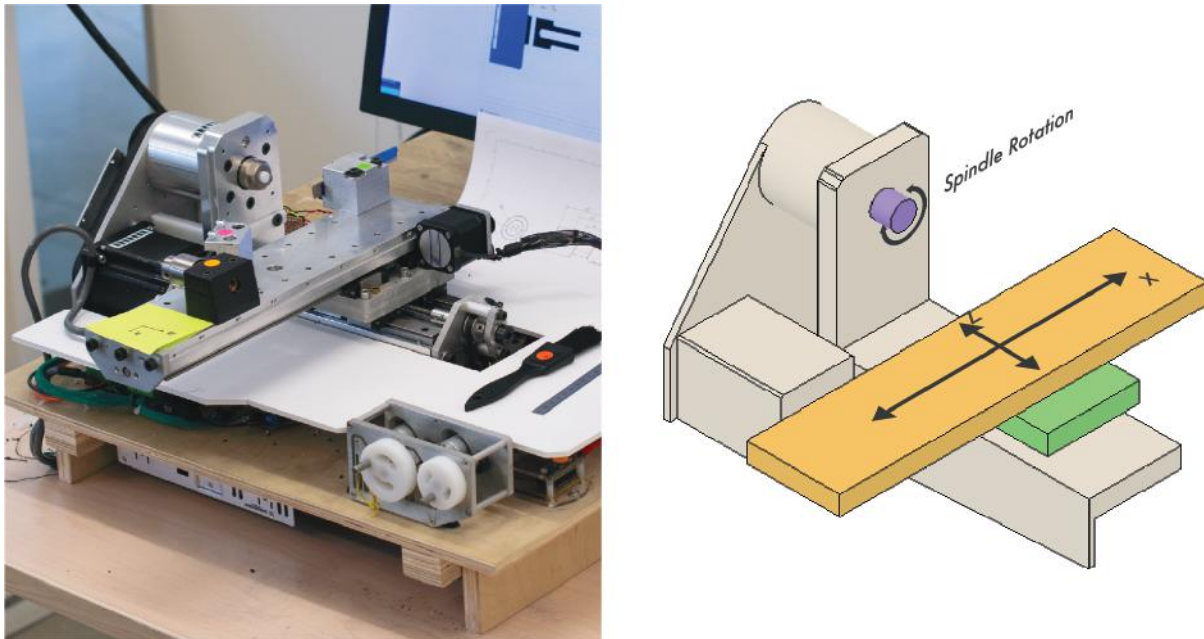


Figure 4.1: Left: Our lathe. A foamcore base was installed during the user study to reduce the visual clutter of the lathe when introducing the tool to new users. Right: Schematic view of the lathe. Geometries to be cut are mounted to the spindle using a collet.



Figure 4.2: Three physical components made using our lathe. From left to right: a miniature chess piece, bowling pin, and Energy Dome.

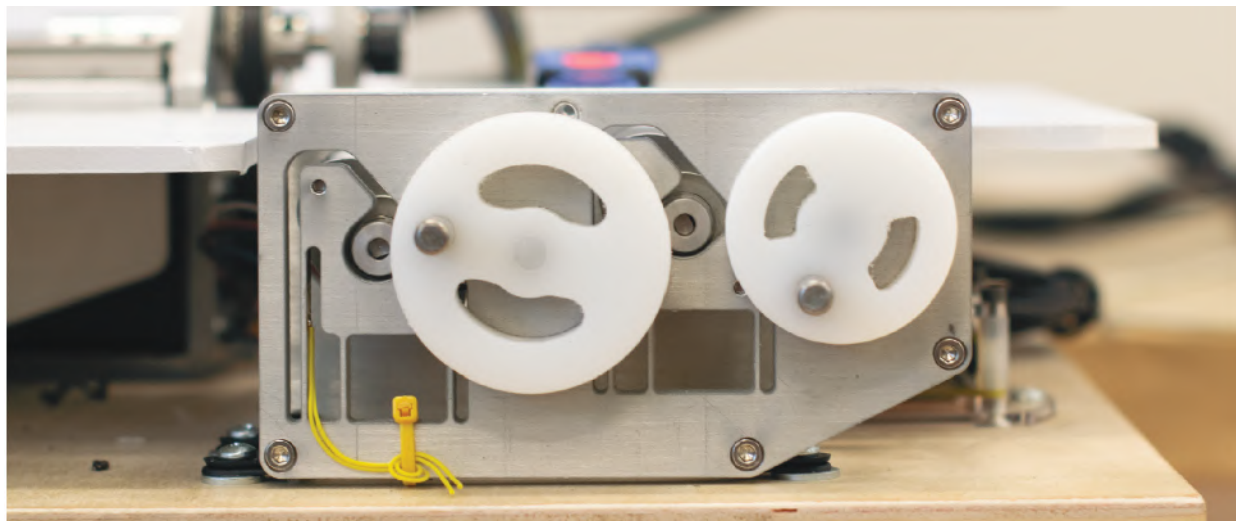


Figure 4.3: Detailed view of the haptic handwheels used for direct control.

## Force Feedback Handwheels

We designed the visual layout of our two handwheels to reference the arrangement found on a traditional lathe: one larger handwheel for controlling the z-axis, and a smaller handwheel positioned to the side and offset above for controlling the x axis (Figure 4.3). In a manual lathe, the handwheels are directly coupled to the motion of the lathe, and the user feels the forces required to move the lathe as these forces are transmitted through the mechanical transmission. In contrast, our handwheels are drive-by-wire; they measure position and output force to the user, but there is no coupling between the handwheel and the lathe other than the ones we design and implement in software. This architecture is the basis for all of the haptic interactions we have developed.

Each handwheel subassembly consists of a handwheel mounted to a rotary shaft, a brushed DC motor with encoder, and a belt drive transmission coupling the DC motor to the handwheel shaft. These components are all mounted to a waterjet aluminum frame (Figure 4.1). For ease of implementation, we currently implement a simple impedance (measure position, output force) type haptic controller for force feedback to the user. The handwheel motors are mounted to flexural stages integrated into the waterjet aluminum frame. This allows direct measurement of the torque output of the motor, such that we could more precisely control the amount of force a user feels through an admittance type haptic controller (measure force, output position).

## “ChipguARd” AR Display

An iPad tablet with a built-in rear-facing camera is placed in front of the workpiece, such that the camera faces the collet and the screen faces the user. The iPad is mounted on a

flexible gooseneck stand which allows the user to move the screen freely to any position and orientation, as shown in Figure 4.4. This setup mimics that of a chipguard in traditional hand lathes, a transparent piece of plastic that sits between the workpiece and the user and prevents cuttings from flying out and damaging the user. In our configuration, the “chipguard is not a transparent panel, but a camera passthrough display. The plastic casing on the back of the device acts as barrier that protects the user from flying chips. More importantly, the passthrough nature allows us to change the relationship between the input to the camera and output on the screen, in realtime. We can computationally “augment” the world by drawing virtual objects on the screen that dont appear in the real world, and thus aren’t observed by the camera. We can also overlay virtual objects on top of real objects, either as an information HUD, or to replace physical objects with virtual ones. Using the tablets sensors (IMU, accelerometer, and rear-facing camera), along with Apples ARKit software framework, we can precisely track the pose of the tablet and accordingly adjust the render to make these virtual objects appear persistently anchored in the physical world. This architecture is the basis for all of the AR interactions we have developed. We call this AR device, mounted to our lathe in a chipguard configuration, the “chipguARd”.

## 4.2 Software Implementation

### Networking

The serial connections on the lathe and handwheel microcontrollers are connected to a Tornado<sup>1</sup> webserver over a UART Serial to WebSocket bridge. The Tornado server coordinates with the microcontrollers to determine the state of operation (status, tool position, etc.) which it then uses to update the geometry of the part being cut. This is stored as a Paper.js<sup>2</sup> visualization, a 2D CSG library which runs on front-end Javascript. Since all parts made on lathes are radially symmetric by-construction, the 2D Bezier path stored in the Paper.js visualization is the minimal representation of the 3D geometry of the part.

A separate Express.js webserver establishes WebSocket connections with each of the AR clients. Over a combination of REST APIs and WebSockets, this server fetches the new geometry from the Paper.js visualization every time an update is made, and routes it to each of the connected AR clients. Each of the clients use this data to independently construct identical 3D geometries. An additional local Python server receives an audio stream from the microphone, and coordinates the real-time voice command detection with Google Cloud. A system diagram for the network architecture is shown in Figure 4.6

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<sup>1</sup><https://www.tornadoweb.org>

<sup>2</sup><http://paperjs.org/>



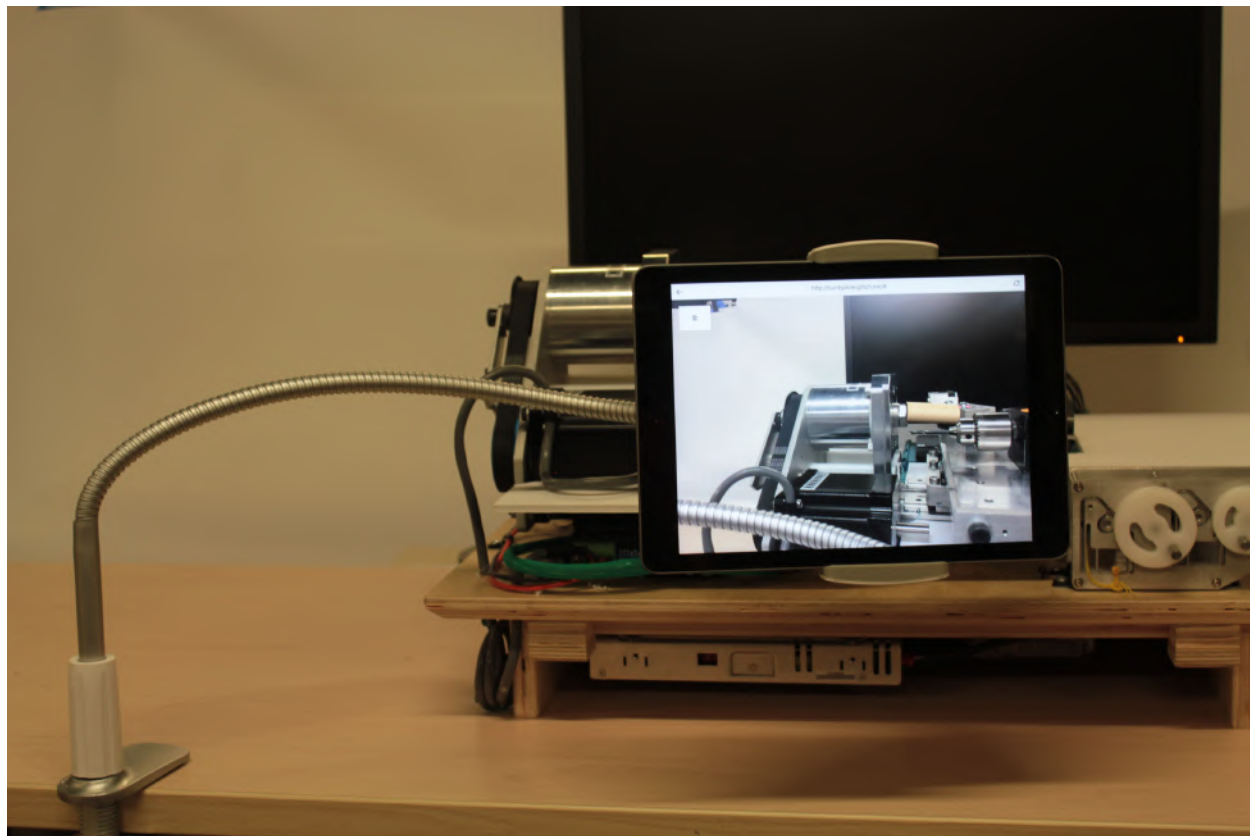


Figure 4.4: The chipguARd system: An iPad attached to a gooseneck stand functioning as a movable AR interface. On the screen is the AR application running; the camera pass through with a virtual wooden work piece is visible on it.

## AR application

The AR application was initially built using Unity3D<sup>3</sup>, a 3D game engine popular with commercial game studios and hobbyist developers alike. Although initially developed for video games, its 3D graphics, realtime physics and intuitive scripting API has made it popular for all kinds of interactive 3D applications, such as simulation and visualization. It supports many AR/VR devices, and has been used to create many popular immersive experiences including Pokemon Go, Beat Saber, and TiltBrush. More than 60% of all AR and VR content is made with Unity [53]. Although we initially started development with Unity we eventually switched for a web-based AR development platform. The build automation tools and continuous deployment solutions for web applications were more mature, more stable, and easier to work with than Unity’s brand new AR/VR integrations. Furthermore, I had personally worked extensively with Unity in the past and was itching to teach myself a new

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<sup>3</sup><https://unity.com>

technology stack.

The final version of the application was built using a Google-developed library called WebARonARKit <sup>4</sup>, which allows developers to build AR experiences using web technologies, at a performance on par with native mobile apps. It is implemented as a fork of the open source Chromium browser with modifications to run ARKit <sup>5</sup>, Apple's first party AR framework for iOS devices. It does this in a two-layer approach, layering a WKWebView running WebVR 1.1 <sup>6</sup> on top of a camera feed running natively. This allows the AR tracking and mapping to run fast as a native app, while simultaneously allowing the graphics and rendering to be browser based. Client-side Javascript in the browser queries ARKit's native localization engine through WebARonARKit's API to get the latest 6DOF pose of the device, and Three.js<sup>7</sup> to render the virtual camera in the scene accordingly.

Updates about the lathe or workpiece are fetched from the Express server. The 2D Bézier-based representation is rotated along its longest axis to generate a 3D shape, then discretized and stored as a 3D mesh. UI elements on a pull-out sidebar menu allow the user to modify and interact with this 3D mesh. The collaborative mode is accessible as another webpage; it is nearly identical to the main application, but presents annotation features instead of some of the fabrication specific features. The different AR clients talk to each other over WebSocket via the Express server to pass data about state, and annotations.

## User Interface

A screenshot from the AR application is shown in Figure 4.5. The major elements of the interface are as follows:

### Camera pass-through

The feed from the rear-facing camera is displayed across the entire screen natively, under the transparent WKWebView.

### Virtual work piece

Using Three.js, the work piece is visualized as a 3D textured mesh. Using the AR capabilities, it is synchronized to rest in the headstock of the physical lathe.

### Sidebar menu

A sidebar on the left side of the screen has options to interact with the work piece. The menu placement was chosen to leave as much screen space as possible to the camera pass-through

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<sup>4</sup><https://github.com/google-ar/WebARonARKit>

<sup>5</sup><https://developer.apple.com/arkit>

<sup>6</sup><https://github.com/immersive-web/webxr>

<sup>7</sup><http://threejs.org>

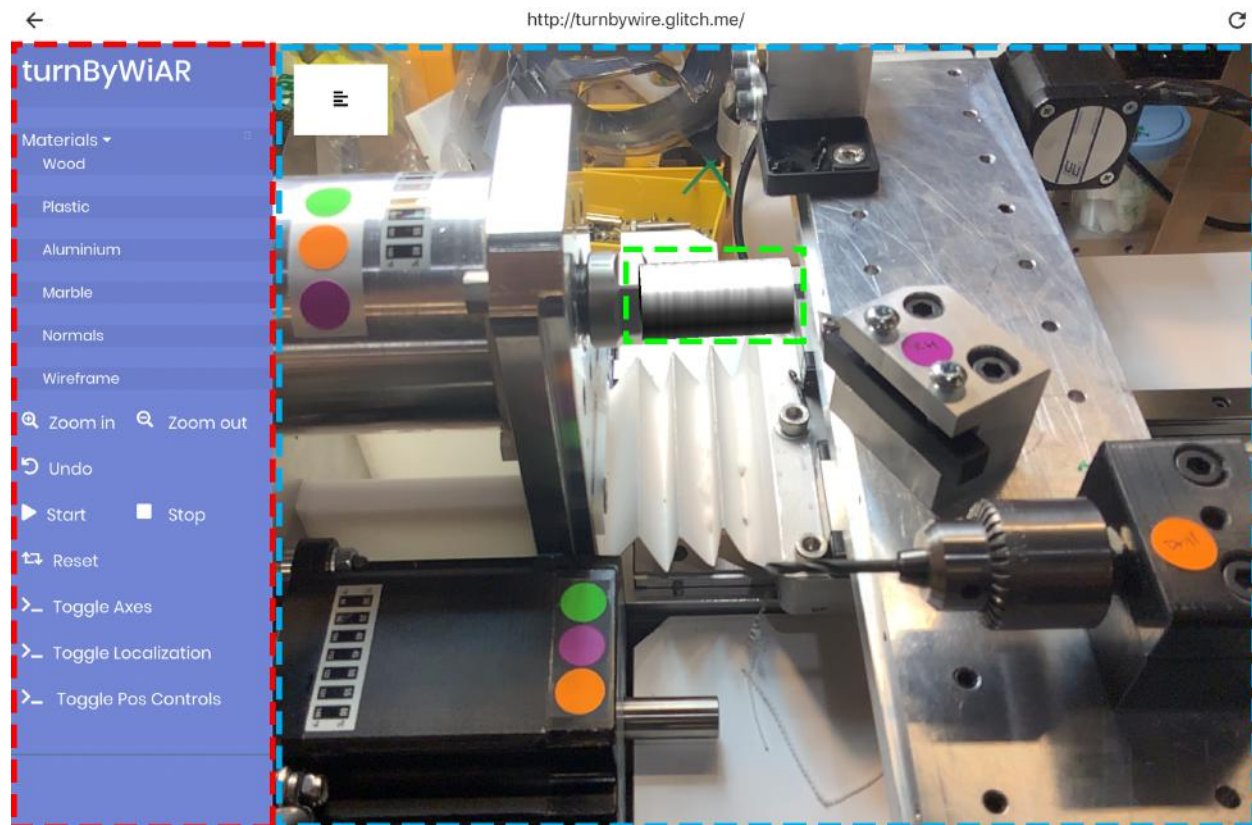


Figure 4.5: The UI for the AR application. Each of the three main sections is outlined with coloured dashed lines. The red section is the sidebar menu, the green section shows the AR render of the virtual work piece, and the blue section shows the pass-through camera feed. The white button in the top-left corner toggles the visibility of the sidebar menu, and expands the field of view of the camera feed proportionately.

view in order to maximize immersion. The visibility of the menu can be toggled with the hamburger button.

### 4.3 Putting it all together

An overview of the entire Turn-by-WiAR system, with the relationship between all of the subsystem, is shown in Figure 4.6.

#### System walkthrough

Here we give a concrete example of how the different elements of the software and hardware work together to enable one of our interactions: haptic snap to guide. The user says “Create

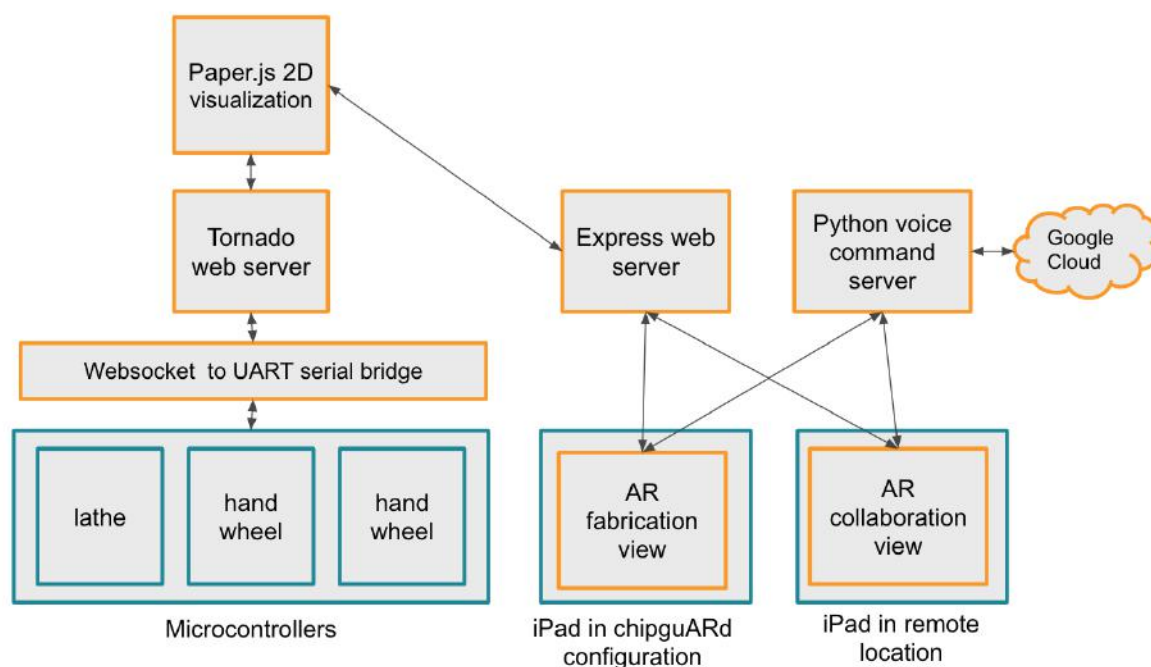


Figure 4.6: System architecture diagram. The hardware components are in blue, the software in orange. Having separate webservers for communication with the lathe hardware and with the AR clients modularizes the architecture and separates the dependencies from the lathe with those for the AR clients.

horizontal guide at 10 mm.” This audio is passed to a local Python service which forwards it to Google Cloud. A voice-to-text service in Google Cloud returns a text transcription, which is parsed on the server to determine that a virtual guide needs to be added, on a certain axis and distance. This data is wrapped in a JSON object and sent to the Express.js server as a HTTP POST request. The Express server passes this message to the client running the 2D Paper.js visualization and each of the AR clients. Each of the AR clients convert the 2D axis and position information into a 3D pose, using the known correspondence between the digital and virtual world and some linear algebra.

Simultaneously, a command is issued to the corresponding handwheels microcontroller to add a virtual detent at that location. This message travels through the WebSocket and is routed to the appropriate hardware serial device by the Tornado WebSocket to Serial web server. Information about the guide locations are redundantly stored on the firmware of the handwheels, the Javascript visualization, and the AR client. When the user rotates the handwheels, the updated tool position is streamed from the microcontroller to the web application. When the users tool approaches a guide the user feels a haptic indication. To achieve this, the guide location is set as the desired position for a simple proportional-derivative (PD) controller by the handwheel microcontroller. As a result, the motor attached to the hand-

wheel is actuated to maintain the handwheel at the desired position. The gains of the PD controller are chosen such that the user will feel the handwheel being pulled toward the guide location, but can insist to move the handwheel away from the desired position. When the user moves the handwheel far enough from the guide, the haptic detente is deactivated. The ‘feel of the detente can be modified by tuning the PD controller (effectively, the virtual linear spring constants).

## Limitations and Mitigations

### Latency

As Figure 4.6 shows, there is a long datapath from the handwheel microcontrollers to the AR render and back. Despite this, we observe in practice an acceptably low latency of around 10 ms. On a standard 2017 model iPad the app runs comfortably at 30 frames per second, even when the radial and depth discretization is set to a miniscule 0.05 millimeters. This is suitably fast to avoid any kind of perceptible lag between the geometry of virtual objects and the real world position seen through the camera feed, for all but the highest cutting tool movement speeds.

### Drift

Lathe turning is a highly precise operation requiring the position of the tool and the part to be accurate to millimeters. However, the AR tracking system has a non-negligible amount of drift, due to dead reckoning in the IMUs, errors in the image processing, and the two-layered timestamp-based synchronization model <sup>8</sup> of WebARonARKit. This drift is especially high when dynamic objects such as cutting tools move through the scene. We mitigate some of the drift error by manually adding feature points (coloured stickers) to the lathe and allowing for manual calibration to fine tune the position. We also disable updating the localization estimate while the handwheels are moving, and re-enable them when they stop. This circumvents the dynamic object problem (otherwise the cutting tool’s linear movement can cause issues), based on the assumption that the user cannot move the iPad at the same time as the handwheels.

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<sup>8</sup><https://github.com/google-ar/WebARonARKit#HowWebARonARKitWorks>

# Chapter 5

## Evaluation

### 5.1 User Experience with Turn-by-WiAR

We were interested in evaluating how participants perceived the various proposed interactions. To do so, we designed a experiment to observe how novice users interacted with the “representing” features and the “extending” features while creating a simple prototype using our system.

#### Participants

Three participants were recruited from the CITRIS Invention Lab, a educational makerspace for students on the UC Berkeley campus. Two were female, one was male. All were between 20 and 22 years old. They all had prior experience with digital fabrication processes, including prototyping with 3D printers, laser cutters and hand tools, but none of them had ever used a lathe before.

#### Procedure

All studies took place in the Hybrid Ecologies Lab, next door to the Invention Lab makerspace. After filling out the appropriate research consent and media release forms, we started the session by showing each participant a series of images of objects fabricated on a lathe, as well as images of various fictional lathe configurations. We used this to launch into a conversation about their prior perceptions around machine safety, exploration and precision around each of these configurations, and discuss which ones they found most appropriate for each task. Then they were introduced to the lathe.

The introduction took the form of a hands-on guided tutorial where I would show the user the various elements of our system: the lathe, the force feedback handwheels, and the AR display, as well as the interactions they could initiate through the wheels and the AR application. Participants were allowed to play with each feature after it was explained to them. After the introduction, they were shown a picture of a chess piece (see Figure 5.1)



Figure 5.1: The sample rook used as inspiration for the participant’s fabrication task. This geometry was chosen because it involves facing and turning, as well as smooth curves. We didn’t introduce them to virtual tools for this task, so they were forced to manually learn a complex two-handed manoeuvre to complete the curve. In addition, chess pieces have a strong aesthetic component which was meant to motivate the participant’s design.

and instructed to prototype an approximation of it using the lathe. No physical material was placed in the lathe; they were designing a solely digital prototype. After the task was completed, they could place their designed AR chess piece on the table to inspect it. Then, we engaged in a semi-structured interview about their experience. In total, the study took about an hour per participant.

## 5.2 Comments

We group comments from the interviews thematically, using the themes we identified as being in conflict with each other in Chapter 1. We show here that participants pick up on and appreciate elements of each of these themes in their interaction with the Turn-by-WiAR system, showing that these tensions can in fact be resolved.

### Exploration

Participants note how their sense of exploration and creativity was foregrounded by many of the features in our system: the use of virtual material, the ability to undo and redo operations, and the extended virtual audio. All the participants expressed that they were more likely to try more things in a digital environment than a physical one:

P3: “Using an actual tool feels more high-stake. With this tool, I can play around with it. It feels like more of a tinkering tool. It feels less dangerous, because it’s all virtual.”

P3: “I think one of my favorite features of this is undo and redo. You can’t do that in real life. Having that ability to go back and fix things or just play around with things, is so unique to this kind

of tool.”

P2 pointed out how it led to less material waste, which made her more likely to try more things. P1 also felt the sense of play evoked, but through the non-diegetic bubble-wrap inspired audio effects.

P1: “I can see how it would make me feel less tense ... feel more, like fun and joy...”

## Manufacturability

Although participants felt a strong desire to create and explore, they were also made aware of the constraints and physical limits of the machine.

All of the participants had their motions stopped at some point by haptic technique scaffolding. The most common error was forgetting that the right handed cutting tool cannot be moved from left-to-right inside the material. P2 explains her process of realizing this constraint: At first, she used to undo tool to try different ways of making it, but then finally realizing that it was it was a limitation with the machine, not with her skill. This anecdote illustrates how the exploration afforded by the undo/redo feature can co-exist with the constraining nature of machine-specificity without overwhelming the user.

P2: “I wanted to do a left shoulder, something that wasn’t fabricatable on the machine. And I tried to undo, but no matter how much I undid I couldn’t fix it. But I guess it’s impossible to design that shape with this tool, so maybe that’s the point.”

P2 also noted how the AR simulation helped her understand the way the machine worked.

P2: “Part of the understanding was definitely -heh- augmented, by the augmented reality app. You told me what a lathe was and how it worked, but I didn’t really understand that or appreciate that if I didn’t see the part rotating, and forming that shape on the AR view. An a 3D CAM software, the design is in one plane, and that doesn’t communicate how the machine actually does it.”

P1 noted how he prefers learning the quirks of the machine in this kind of virtual mode than directly, because it was faster than doing so manually:

P1: “The general way is to learn a tool is to by practicing cutting tens of them before you really get the motions down. Being able to use the AR tool to practice is um, really cool.”



## Materiality

Even though the participants noted that the computer-generated graphics didn't convey the full depth of real-life materials, they still felt like they could directly access many of the material properties.

P1: "When I see textures on computer screens, they always seems gimmicky. Like, renderings are supposed to look as real as possible, but you can always tell they're not real. ... But being able to see the shavings are really useful because you can tell exactly when the lathe starts cutting."

P2: "I did like the sounds in the app. I think sounds - squeaking, cracking are really important to understand what's going on. When you're sawing, for example, you can't always see where the tool is but you can tell that it's not doing what it's supposed to do based on the sounds."

P1: "Even though I really liked the bubble wrap based sound, it made me think that the material was less dense. Even though I got the haptics. So that's something worth thinking about?"

P3 realized how this instant material transformation would drastically simplify her prototyping pipeline:

P3: "Being able to take that shape and place it in your environment is really useful. Being able to see how things work together, for artistic projects, being able to visualize how everything looks. It's so easy to toggle between different materials. Otherwise I'd imagine you'd have to build individual prototypes with each materials to see that, and that would be unfeasible."

She also valued how it allowed her to start thinking about material properties much earlier in the design cycle.

P3: "When I prototype, it's mostly always laser cutting, so I end up just using wood. If I wanted to take it past a prototype, I'd probably start thinking about which materials, do research into their properties and and looks and look more into that ... But with this, I can have those discussions (about material selection) early."

At the same time, two of the participants noted that seeing the materials weren't always valued, and could be distracting. P2 noted that the distracting nature of material is true even in real life, and that many auditory cues can be just "noise": uninformative and annoying.

P1: "If I had a design that I knew I wanted to cut, I'd probably just look at the plan view, on the screen. Because the AR screen has a lot going on, with the materials and everything, whereas the 2D plan view is just black and white."

P2: "With shop tools, I try to cancel out audio. If I have noise-cancelling headphones then I'll use those. I don't feel like I've ever gotten anything useful from audio cues."

Although she didn't find the virtual audio as useful as P1, she did appreciate the fact that you could just mute it, something you couldn't do with physical tools. Additionally, she saw the extended virtual audio as a way of tuning up the signal-to-noise ratio, of cutting sounds. After the interview, we informally discussed the possibility of embedding these sound wave transformations directly into the music on her MP3 player, and she expressed excitement at the possibility of being able to listen to her music while also having an ear out for (the most useful of ) material transformations.

P2: "I think it's kind of fun! It was better than hearing what I would in real life, because that's mostly just noise. This is like you can express the language of the wood more clearly."

## Precision

All of the participants used virtual guides at least once while prototyping their part, to ensure that the straight cuts was exactly where they wanted it. One of the participants additionally enabled the secondary guides.

Interestingly, P1 noted that he felt that his operations were *more* precise with handtools than with CAD.

P1: "I think this is something universal about digital design is that you're less precise, because there's like nothing at stake. It allows a lot of creative freedom, but also we're more sloppy and I think people don't always see that."



Figure 5.2: Participant from the user study using the Turn-by-WiAR system.

# Chapter 6

## Discussion

### 6.1 Novel prototyping workflows

Although the user study was meant to explore how people interact with the new making metaphors leveraged by Turn-by-WiAR, we also envision a number of new workflows that might emerge from such a hybrid virtual-physical machine. We explain three such workflows below.

#### **Design-Fabricate-Iterate**

This is the standard design cycle. CAD packages (including our chipguARd application) are used to generate a digital 3D model. This file is sent to a CNC machine and after some manufacturability checks, the part is physically fabricated. Then the part is manually inspected and tested by users. This cycle is repeated until satisfaction. ChipguARd ports some of the properties of the fabricated object into the design stage itself, making it easier to detect errors early and reducing the number of iterations needed. By foregrounding material and machine considerations in the design stage itself, it gives the user more information at hand, allowing them to reach flow states while designing [10].

#### **Incremental Design and Fabricate**

In this workflow, chipguARd is used to project virtual material alongside physical material in the lathe. Designs can be tried and tested on the virtual model, then when the user is satisfied, they can be immediately copy/pasted onto the physical material. This workflow enables incremental iteration between design and fabrication, instead of designing the entire part pre-fabrication. This incremental design and testing is a common practice among programmers and electronicists but has been historically unavailable to material practitioners due to the constraints of working with matter. In software development, it is a common practice to test individual functions and methods before composing them together. This kind of modularity allows for errors to be caught early on and prevent longer term errors. It

also provides emotional benefit through incremental satisfaction rather than one big disappointment at the end [52]. Anyone who's written hundreds of lines of untested code only to see multiple errors at compilation time is well-aware of this feeling. Similarly, circuit builders will use unit testing in their physical practice to identify errors. Overall, this kind of incremental design de-risks later stages of the prototyping process, and therefore can embolden the user to make riskier, creative decisions in their design.

## Augmented Fabrication

In this configuration, the chipguARd is used to composite digital information on top of the physical piece. For example, a virtual grid can be superimposed on top of the physical model to visualize dimensions in-situ. At the same time, it allows for a more critical things. For example, a practitioner may be skilled with working with wood, but not familiar with the properties of metal. By superimposing, say, a virtual wooden piece on top of the physical metal material, they can cut the metal while receiving the visual, auditory and haptic cues of the wood material, to which they are accustomed to.

## 6.2 Future work

### Head mounted displays

We believe that using a head-mounted AR device such as the Microsoft HoloLens or the Magic Leap One instead of a mobile AR device will create more opportunities for AR integration. While such a device would break the chipguard metaphor, it would be hands-free, allowing the remote operator to manipulate physical objects with their hands while viewing the virtual model from multiple points of view. Additionally, the binocular depth cues afforded by the stereoscopic displays on these devices would better help the operator judge 3D depth, which would be useful to more intuitively sense the position of the virtual object in 3D space (see Figure 6.1.) This would only marginally help the fabricator view (they are mainly interested in relative depth, which is dominated by occlusion cues), but would help the collaborator with judging fit in-situ, especially in cluttered environments.

### Augmented collaboration

Our system provides a number of scaffolds that de-risk operations as the fabrications operates: hard stops on joint limits, visual and haptic guides, the ability to undo/redo, for example. We are also interested in exploring what virtual scaffolding might look like on the collaborators view. For example, the AR systems knowledge of the environmental geometry might be used to automatically dimension real-world parts, or snap the virtual model to flat surfaces. A more sophisticated form of scaffolding would be to mediate the interaction between the virtual part and physical parts, for example by snapping the virtual model to



Figure 6.1: A user views the virtual work piece on the Turn-by-WiARlathe through the Microsoft HoloLens AR headset.

physical parts it might join to, and keeping them together as they are moved. We could even do real-time finite element analysis or physics simulation using a game engine like Unity3D to test structural integrity of the designed part in the physical environment. Instead of uniting the remote collaborator’s and fabricator’s view of the world, by augmenting them in different ways we can synergistically enhance the efficiency of the collaboration.

## Intelligent undo/redo

Based on the feedback from the user experiment, we see undo/redo being a powerful digital metaphor when applied to fabrication. However there are still open questions on the best way to design them. Digital documents have discrete operations that easily lend themselves to undo/redo operations. However, continuous real-world processes have no such analog, making the “unit of an undo harder to define. In this work, we chose a temporal unit, but other design possibilities exist. In particular, it would be interesting to design a checkpoint-based undo system in which the users could define their own units of operation. A machine could use these user-initiated checkpoints to learn the optimal unit on a per-user per-workflow

basis. This might also serve as a starting point to explore non-linear design exploration.

## Generalizing to other tools

In this paper we built a lathe. We are interested in how this approach can be generalized across other fabrication tools. Our approach is most easily extensible to tools with mechanically transmitted inputs (as opposed to tools where the user works directly with the material), and planar cartesian motion. For example, table saws, band saws, drill presses, and planers could all be augmented by our haptics plus AR approach.

We are also interested in exploring how similar ideas can extend to more general workshop tools, with unconstrained inputs and outputs. In the case of, say hammers, chisels, and sandpapers, their unconstrained motion make it harder to (1) deliver realistic force feedback, and (2) compute the real-time physics based mesh deformation on the virtual materials.

## 6.3 Conclusion

The primary contribution of this work is the synthesis of digital fabrication tools with by-wire haptics and augmented reality for input and output. Specifically, we use these two modalities to achieve three goals: to represent, extend, and merge perceived fabrication realities. In doing so, we foreground the importance of material and machine in the design process, and reframe machine shop tools as interactive digital agents that simultaneously scaffold learning and provide sites for creativity. This framing aims to center the human in the process of prototype generation, and leverage our capacity for embodied interaction through vision, hearing, speech, haptics and kinesthetics. Finally, we suggest ways that these augmented tools can and should repurpose existing digital and physical metaphors to extend the workflows with which we engage with computationally-driven *making*.

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