Fabricatable Machines: A Toolkit for Building Digital Fabrication Machines

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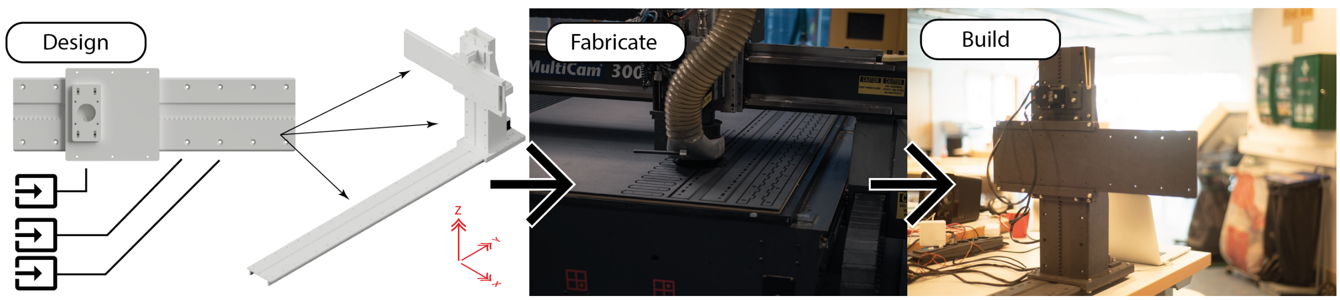

Figure 1: This is Fabricatable Machines. A toolkit that lets users design, fabricate and build custom digital fabrication machines. We implemented a linear actuator, The Fabricatable Axis, that is both parametrically sized and optimized to be manufactured using a CNC milling machine. Users can prototype and explore combinations of linear motion virtually using the parametric CAD model, before fabricating and assembling their design.

ABSTRACT

Digital fabrication is changing the way we design and manufacture the objects around us. Digital fabrication machines enable mass-customisation. However, customising the machines themselves requires a high amount of expertise, which prevents even advanced users from taking part in the creation of bespoke fabrication tools. We present Fabricatable Machines, an open-source toolkit for designing custom fabrication machines. We designed a linear motion module, The Fabricatable Axis, that provides robust automated linear motion. The Fabricatable Axis can be resized, adjusted, and fabricated from different materials. Users can build machines by combining multiple axes. We optimised the design of the axis to be manufactured using a CNC mill, with few externally sourced parts. We observed users creating machines including portable milling machines, 3D printers, and pipe inspection robots using the Fabricatable Machines Toolkit.

TEI '20, February 9–12, 2020, Sydney, NSW, Australia

ACM ISBN 978-1-4503-6107-1/20/02…$15.00
https://doi.org/10.1145/3374920.3374929

CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**; • **Applied computing** → **Computer-aided manufacturing**.

KEYWORDS

Digital Fabrication, Machine Building, CNC, CAD/CAM

ACM Reference Format:
Frikk H Fossdal, Jens Dyvik, Jakob Anders Nilsson, Jon Nordby, Torbjørn Nordvik Helgesen, Rogardt Heldal, and Nadya Peek. 2020. Fabricatable Machines: A Toolkit for Building Digital Fabrication Machines. In *Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '20), February 9–12, 2020, Sydney, NSW, Australia.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3374920.3374929

1 INTRODUCTION

Digital fabrication tools such as 3D printers, computer-numerically controlled (CNC) milling machines, and laser cutters are becoming widely available, ranging from consumer to industrial versions. These tools are changing the way that people design, produce and interact with objects and devices [11]. This has sparked interest from HCI researchers into fabrication interactions and workflows [23].

However, digital fabrication machines themselves are hard to modify or be tailored by their end users. It is difficult to modify the work envelope, customize the motion control, or use different end-effectors than the machine was designed with. Customising, integrating, and extending machines could expand the capabilities of individuals and communities to build more machines to increase production, to build cheaper machines to increase availability, or to build specialized machines tailored for specific purposes. In particular, lowering the threshold to building specialized machines could make it easier to experiment with novel fabrication workflows.

The increased accessibility of fabrication technology will mean that new types of users will be engaging with fabrication. These new users will require different kinds of fabrication workflows than their historically industrial predecessors. Developing novel fabrication workflows for these newcomers to fabrication is an important HCI research question. To facilitate this kind of exploration, Fabricatable Machines aims to provide scaffolding and infrastructure for designing custom computer-controlled machines. Our goal is to enable users without expertise in machine design but with application and domain expertise to develop their own novel machines.

If we investigate the main components of these machines we see that the majority of them consist of combinations of linear motion modules, or linear axes, that together makes a tool move around in space. Different machines will have different arrangements of these axes, depending on the type of machine. For example, most of today's commercial 3D printers consist of three linear axes that together make a plastic-depositing tool move around in Cartesian space. A laser cutter consists of two axes that makes its tool move in X Y, and one Z axes that controls the focus (distance to material) of the laser beam. To tailor and create such machines from scratch requires expertise within several different engineering domains and a broad supply chain of parts. Can we encapsulate part of this machine design expertise into a toolkit?

To achieve this, the Fabricatable Machines toolkit provides modular, parametric machine parts that can be customized and assembled into machines. Our approach is inspired by the Cardboard Machine Kit [29], which uses standard-sized cardboard linear stages as a building block for different machine configurations. The Cardboard Machine Kit authors demonstrate that even novice machine builders were able to create very different kinds of machines using this system [29]. However, cardboard is a temporary and flexible building material, not well suited to many applications. Furthermore, the standard size of the linear stage of the Cardboard Machine Kit poses a big limitation on the work envelope. Users would benefit from modular parametric building blocks that streamline the machine building process.

The Fabricatable Machines toolkit aims to provide a streamlined workflow for designing robust parametric machines. It provides modular machine parts that can be customized, fabricated, and assembled into functioning digital fabrication machines. These machines are *fabricatable*, meaning they can be made using a standard set of existing computer-controlled machines, and with minimal use of special parts, processes, or skills.

The *Fabricatable Axis* is a modular building block that gives the user high-force customizable linear motion. We implemented the Fabricatable Axis as a parametric CAD model, making it easy for target users to customize. Our system allows the user to customize the width, length, speeds, and force to suit their needs. The design is optimized to be manufactured using CNC milling machines, to use a minimum of externally sourced parts, and to be made out of a large variety of materials. Users can build more complex machines by combining multiple instances of the axes. The Fabricatable Machines project is documented in an online repository, which includes detailed technical descriptions, walk-throughs, documentation of existing machines, and the source files for the parametric axis. We argue that Fabricatable Machines lowers the threshold to producing custom machines, scaffolds users into the machine design and tuning, and fosters a unique community of practitioners.

Our research question is: *Can we provide a toolkit that allows our users to create machines of different sizes, out of different materials, for different speeds and forces, without heavily relying on external supply chains?* The main contributions we make towards this goal are:

- Software tools that encapsulate domain expertise for creating and fabricating linear motion modules.

- A mechanical design which is optimized to be fabricated using a CNC milling machine.
- An online open-source repository that documents machines that have been designed with these software tools and fabricated in maker spaces.

Our target users for the toolkit have access to and prior knowledge of digital fabrication tools. They are interested in a particular application for which they need precise motion control. However, they do not necessarily have prior knowledge of machine design. For example, they might be members of a makerspace who have developed a novel workflow they would like to make more robust, or scientists that need to take repeated measurements, or artists experimenting with combining craft and automation.

In particular, we seek to provide HCI researchers with better infrastructure to explore future possibilities of fabrication such as interactive fabrication [42] and pervasive fabrication [5]. Designing, making, and implementing bespoke and robust machines is a time consuming and challenging endeavour. By encapsulating the domain knowledge required to implement a machine design into a tool, we aim to provide scaffolding infrastructure that enables HCI researchers to explore novel workflows in fabrication.

In this paper, we provide detail on the design and implementation of Fabricatable Machines, including the parametric model, the layout and tuning documentation, and the online repository. We will also detail several machines that were built by users in the wild.

2 RELATED WORK

As fabrication technology such as 3D printers become increasingly widespread, understanding how new users will interact with these machines has become a salient HCI research topic [23]. Previous work has shown the benefits and the need of allowing end-users to tailor and customize their own machine interactions. For example, Hudson used an existing 3D printer to which they attached a new end-effector to be able to print with yarn [16]. Oxman et al. used an existing CNC mill with a novel head to be able to weave silk [28]. Teibrich et al. added an additional end-effector to an existing 3D printer to be able to use the same platform for subtractive and additive processes [38]. Umapathi et al. trick a laser cutter's driver to run out-of-focus to be able to 'weld' material as well as cut [40], and Ando et al. released an OpenFrameworks toolkit for circumventing laser cutter driver settings to be able to laser cut on curved surfaces [1]. Adding functionality to 3D printers for interactive or hybrid fabrication has also been achieved [10, 31]. Yet 'hacking' limits researchers to modifications that can be made to only existing platforms.

We see our contributions relating to many other active areas of research in HCI, including novel fabrication workflows, novel fabrication machines, end-user CAD tools, fabrication toolkits, and Open-source hardware. In the Fab@CHI workshop, the conveners highlighted a need for domain-specific design and interface tools [23] which we seek to extend beyond the interface to the machine itself. We also strongly draw from maker space, open-source hardware, and machine-building communities, such as the developers of Rep-Rap 3D printers and related components. In the workshop "Fabrication & HCI: Hobbyist Making, Industrial Production, and Beyond" the conveners highlight the intertwining of maker communities and industrial production [8] and how this is leading to alternative fabrication methods. We specifically aim to facilitate the creation of those novel fabrication processes.

Tailoring

Customization, integration, and extension are three levels of end-user tailoring identified by Mørch et al. in the 90s in an analysis of the tailoring of software applications [25]. User skills were observed to be directly mapped to tailoring power, ranging from workers using software applications, to tinkerers linking together modules within the application, to programmers extending software applications [18]. We find that these forms of end-user tailoring have analogies in machine building. Just as it was impossible to design software that was appropriate for all users and all situations, we find that it is now impossible to design machines that are appropriate for all users in all situations. The categories of users that existed for software applications in the 90s now also pertain to digital fabrication: ranging from workers using machines, to tinkerers hacking machines, to machine experts designing machines. Fabrication researchers would benefit from tools to facilitate machine customization, design, and building; Fabricatable Machines aims to provide these.

Robotic Construction in Architecture

Architectural researcher Achim Menges identifies the second wave of digital fabrication to be "*a transition from job-specific computer controlled machinery to more generic production robots*" [24]. Menges joins other architecture researchers and practitioners such as Gramazio and Kohler, Snøhetta, and Zaha Hadid Architects in repurposing industrial robot arms designed for repetitive tasks for architectural practice [2, 6, 12]. He continues: *"This generic character of the basic robotic hardware — that only becomes specific when equipped with a particular effector and tool — enables the design of new fabrication processes prior or in parallel to a specific project, and thus potentially challenges the conventional hierarchy and sequences still predominant in design and fabrication"*. This approach is facilitated by infrastructural work for robotic arm end-effector development such as the Robotic Tool Adaptor and related sensor systems [3, 32]. However, robotic arms are still a formidable investment, and their cantilevered kinematics make them less well suited to tasks that may require high speed, high stiffness, or high forces. Furthermore, due to the complexity of inverse kinematics for robotic arms, toolpath-planning is much more complex than for gantry-based systems. We therefore suggest that "*generic production robots*" could also be made with more conventional motion platforms, lowering cost and complexity. Fabricatable machines aims to provide a toolkit for making these motion platforms.

Fabrication Machines in HCI

Custom making of entirely novel machines has been investigated in HCI research previously, as shown in Zoran et al.'s FreeD [43], Rivers et al.'s position correcting tools [35], Peek and Moyer's portable Popfab [30], or Tian et al.'s woodworking-specific MatchSticks [39]. These novel machines make entirely novel interaction and interfaces for fabrication possible. However, this requires researchers interested in developing novel fabrication interactions to also be experts in machine building. The Cardboard Machine Kit enables the building of cardboard prototype machines [29], but with our system we aim to lower the threshold to making robust machines. Furthermore, it is difficult for other interaction researchers interested in developing novel workflows for these new machines to replicate these custom machines and their setup. With our system we aim to make it easier for researchers to replicate and reuse motion platforms by providing something akin to a software library specifically for machine making.

End-user CAD Tools

We are indebted to Hofman et al.'s framing of the need for CAD tools that use an end-user program perspective [14]. In their framework PARTs, they provide users with familiarity but not expertise in CAD with tools to more easily express and reuse 3D design intent. In 1992, Gantt and Nardi wrote about the different roles different levels of users of CAD may take on within a single organization and how 'local developers' provide support [9]. Since then, the role of 'local developer' has perhaps mostly moved online, but we believe the 'gardener' role now has also taken on the development and maintenance of third-party CAD plugins (E.g. for Autodesk's app store or Food4Rhino [7]). Grafter is another example of an end-user CAD tool; it encapsulates the complexity of mechanisms to ease their reuse [36]. Drawing from this related work, Fabricatable Machines aims to encapsulate machine design expertise in an abstraction that is more accessible to an end-user.

Fabrication Toolkits

Encapsulating subject matter expertise into toolkits is an active research topic in robotics and fabrication. We are inspired by the open-source work by Holland et al. who released the Soft Robotics Toolkit (SRT) [15]. Oh et al. encapsulate information on mechanisms into their toolkit FoldMecha [26], enabling an end-user approach to adding motion to papercraft. Mehta et al. enable the design of robots from functional specifications in their work on end-to-end systems for printable robots [22]. Our toolkit differs from this related work in its application to digital fabrication machines.

Open-Source Hardware

Our work is closely related to and builds upon other open-source machine building efforts. RepRap and the Fab@Home are foundations in the open-source machine space [19, 34, 41]. New machines such as Maslow CNC [21] or the Prusa 3D printer embody what we believe to be best practices for online and distributed community development of machines. Companies who sell machine-building parts in low-volume such as Openbuilds [27] are reducing the need for open-source designs to not rely on external supply chains (this is in contrast to their industrial counterparts such as RexRoth [4] which are difficult for individuals to source). However, we differ from most of these existing machine building efforts in that Fabricatable Machines is focused on motion platforms rather than specific end-effectors.

3 FABRICATABLE MACHINES

The Fabricatable Machines project main contributions are the toolkit for generating linear modules together with the online documentation explaining how to use the tool, hosted at https://github.com/fellesverkstedet/fabricatable-machines. The Fabricatable Axis exists as a parametric CAD model implemented in Grasshopper, a plugin to the CAD tool Rhino. This is a popular software in the maker and design community, which is a large motivation for using it (the software implementation is explained in detail in 4). It also simplifies the process of sharing the tool and allowing users to quickly start designing.

We do not expect our users to know and understand the full curriculum behind the properties driving the mechanical design of The Fabricatable Axis or the different machine designs in the repository. We see our approach to machine design to be analogous to how software developers may use APIs. The API provides access to the functionality of the program without exposing the user to its full complexity. The online documentation and examples gives the users context and an encyclopedia for the implementation. Ultimately, we want to encourage users to experiment and play with the parameters of the model, and by interacting with the

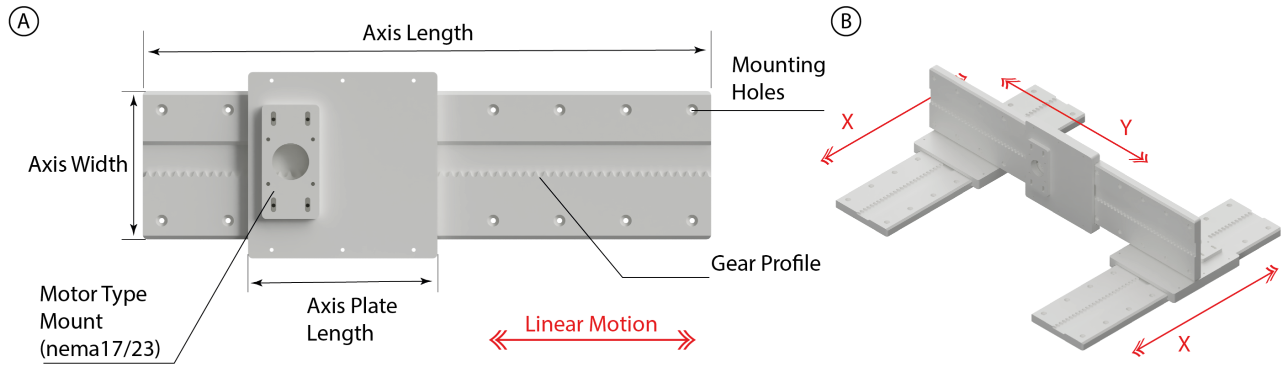

Figure 2: (A) Different parameters a user can adjust to change the characteristics of a Fabricatable Axis. (B) Three instances of the Fabricatable Axis assembled into a machine with two degrees of freedom. A and B show a typical workflow using the toolkit: 1 - Generate required axes, 2 - assemble axes to form the machine design.

model, learn and adapt the principles behind our design. A large effort has been put into documenting how to use the parametric model, walk-throughs of existing implementations of machines, and the technical details of the mechanical design itself. This documentation is available in an online repository.

The Fabricatable Axis

To generate instances of the Fabricatable Axis, the user downloads the 3D model from the repository and imports it into Rhino. The user is met with a default setup of an axis when opening the 3D model, and interacts and modifies the model by changing the input parameters in the grasshopper script.

The parametric model uses constraints and relationships between the different geometrical operations to generate the entire drive train geometry that consists of a linear rail and glide block moving on top of it. Parametric CAD models are like small programs, where the parameters are inputs that drive how the CAD programs calculate the output geometry. By constraining the user to only a key set of parameters, the process of designing and using the axis in a CAD environment is significantly simplified. For example, if the user changes the length property of the axis, the number of rack and pinion teeth are increased. If the user changes the material thickness, the glide block updates the geometry to accommodate the new size.

By only exposing the users to a key set of parameters, we hide the total complexity of the parametric CAD model. In this way we encapsulate the expert knowledge that is behind implementing an linear actuator, and allow machine building novices to use and interact with the model. By interacting and tuning the parameters, users are able to use the toolkit to adjust, adapt and customize a linear axis, without really needing to understand the complex underlying geometrical operations that are performed by the CAD program. The total complexity of the parametric model can be seen in Figure 4A. Users only need to modify parameters on the left to generate output geometry.

We rely on CNC milling machines to fabricate the axes. The final output of the parametric model is sheets where all the parts of an axis are nested together (This is shown in Figure 4 C).

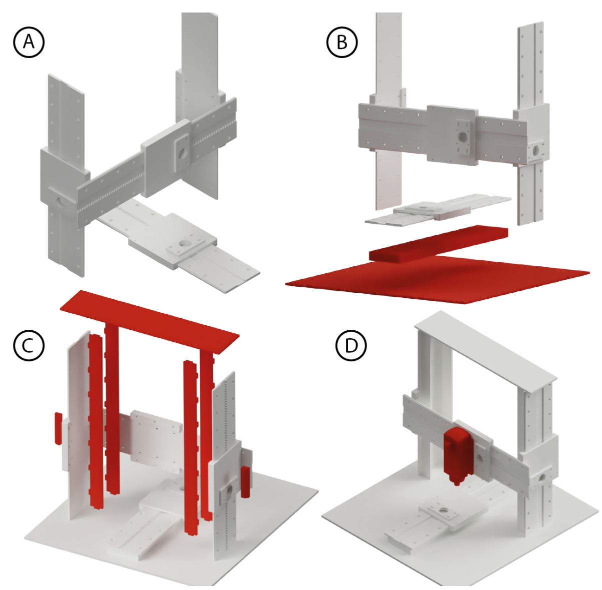

Figure 3: Going from individual instances of The Fabricatable Axis to a complete milling machine. First the instances are positioned manually in CAD (A). Secondly a build plate and a base are added (B). Then to make the Z axes more stiff, they are fitted with a beam structure with tabs (C). Finally a spindle is added as an end-effector (D).

Layout: Creating a Fabricatable Machine

Going from individual linear actuators to a robust and functional fabrication machine is a challenge. Currently our toolkit does not support automatic generation of machine composition, and joining the axes into a complete machine design is done manually. Our target users will normally have a very clear idea of what kind of machine they require. They will know what their target application is (if it is a laser cutter, 3D printer, etc), what work envelope they require and what precision the machine needs to have. Based on this they can use the grasshopper tool to generate the axes they require, position them correctly in CAD and prototype and explore their machine design virtually (as shown in Figure 2).

As a final step, users now have a choice of modelling the fixture and fasteners between the individual axes. Users that are comfortable in CAD can do this virtually in the CAD program. More inexperienced users can fabricate the axes individually, and use the predefined mounting holes together with screws and fasteners to assemble the stages manually. The repository holds information and examples about how such fasteners can be modelled, and thorough explanations of the driving engineering principles behind them.

Documentation and online repository

Fabricatable Machines is thoroughly documented in an actively maintained repository online. In addition to the parametric models of the Fabricatable Axis, the repository includes broad documentation of motivation, tutorials for machine building and tuning, walk-throughs, and detailed implementation documentation of existing machines. In general, our approach to documentation has been to continuously publicly document our progress, rather than refine a design privately and then push a full design iteration to the repository. Past iterations of machines are preserved as historical examples as they are replaced by new versions. This has enabled quick onboarding into machine building for newcomers, as they can read through past issues that were encountered. This openness and public acknowledgement of mistakes has lowered the threshold for newcomers to contribute to the project, and we have enjoyed growing the community of machine builders.

4 IMPLEMENTATION

Our implementation consists of the software written in Grasshopper that generates the Fabricatable Axis and the mechanical design of the Fabricatable Axis. In addition we have included details about electronic and control and a estimated bill of material for a single axis. In this section we will provide details.

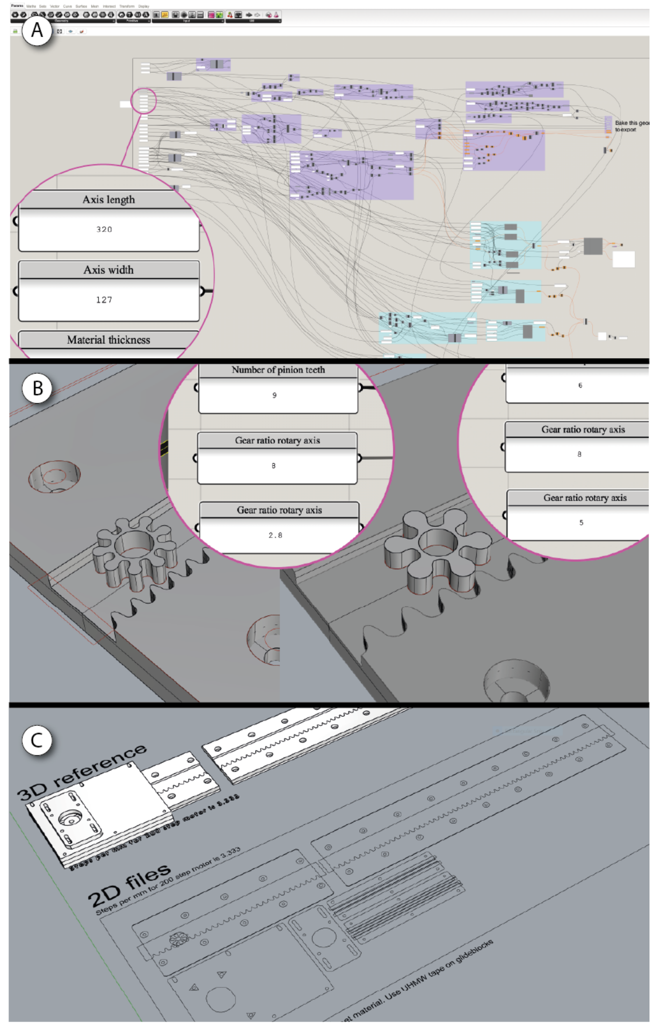

Figure 4: (A) Overview and detail of the parametric model of the Fabricatable Axis implemented in Grasshopper. The model is large and complex, but the user can interact with it and generate axes using only the initial input parameters. (B) By adjusting the input parameters of the rack and pinion geometry the user can tune the characteristics of the drive train. The Rhino viewport updates automatically with the geometry input by the user in Grasshopper nodes (shown in inset circles). By changing properties such as number of pinion teeth or gear ratio, the user can tune attributes of the machine such as its speed or applied force. (C) Example output geometry in Rhino given the Grasshopper Fabricatable Axis program. The model generates both 3D geometry as well as a 2D layout on cut sheets.

Software

The Fabricatable Axis implementation in Grasshopper takes input parameters from the user in initial input-panel nodes, which are grouped on the left of the Grasshopper canvas. Part of the Grasshopper program and an inset of the parameters are shown in Figure 4A. These parameters include numerical values such as axis width, axis length, material thickness, pinion sizing, number of pinion teeth, Boolean values such as whether to include features such as flats, and list selections such as which motor size is being used (e.g. Nema 17, Nema 23). The parameters are pre-populated with default values. As the user updates any of the parameters in Grasshopper, Rhino will immediately render the options in its viewport. For example, as the user updates the number of pinion teeth and their gear ratio, this automatically updates the geometry displayed in the viewport. Softer materials need larger teeth for force distribution. This detail is shown in Figure 4 B.

The Grasshopper program creates both 3D geometry of the axis as well as a lay out of the 2D geometry on a cut sheet. The user can at this point either directly tool path and cut the 2D geometry, or incorporate the 3D geometry into another model.

In addition to the Grasshopper implementation, there is also an implementation in Autodesk Fusion 360. By interacting with the parameter interface in Fusion, the user can change and tune the driving parameters of the axis, just as with the Grasshopper Model. As the geometry of the axis changes, Fusion360 updates and generates tool path files through its CAM (computer aided manufacturing) tool.

Mechanical design

The mechanical design of the Fabricatable Axis is optimized to use as few sourced parts as possible, and to be fabricated from different materials. Making a drivetrain that is scalable, robust, and easy to fabricate requires balancing between many conflicting design factors.

The motion of the axis consists of a rack and pinion drivetrain and glideblocks as a linear motion guide. The geometry of both the rack and the pinion gear is designed to be milled on a 3-axis CNC machine, and is milled directly into the same sheet stock as the frame. The rack and pinion geometry is based on a cycloidal geometry to optimize it for being fabricated with a CNC mill (it takes into account the diameter of the end-mill the user is fabricating with). This differs from the commonly used involute geometry that is found in most industrial rack and pinion systems. The cycloid geometry can be seen in Figure 4B. By having a low gear diameter we are able to run the drive setup with relatively high performance, avoiding the need for a gearbox.

There are two bearing designs for the Fabricatable Axis, a glideblock based design, and a more traditional bearing design using ball bearings. The glideblock design uses polyethylene tape to reduce friction between the glideblock and axis rail, and the pressure it exceeds on the rail is adjusted by moving a slotted wedge. This design provides sufficient friction reduction for applications with low cutting force such as 3D printers, PCB mills, or laser cutters. However, for higher loads such as seen in CNC milling, we have an alternative design that relies on ball bearings for friction reduction. We use 625 or 608 ball bearings, which are also used in applications such as inline skates. This design includes eccentric nuts to adjust the pressure on the guide rail. The roller bearing design can be used for low-friction applications as well, but we still included the glideblock design for cases where reducing the number of line items in the design is more important than reducing friction.

Electronics and controls

As a final step each axis is fitted with a motor and a controller. Fabricatable Machines use standard-sized stepper motors and rely on open-source G-code interpreters and controllers such as GRBL, Marlin, Replicape, Smoothieboard, and Octoprint[13, 17, 20, 33, 37] We use both open-loop steppers and steppers with added closed-loop controllers. When a user has made an single axis, or a composition of axes as a machine, these control boards needs to be set and tuned to the particular axis geometry the user has implemented. For example, the number of steps to move each millimeter needs to be calibrated in terms of the geometry of the rack and pinion geometry. The repository holds information about these steps, and how the input parameters in the parametric model can be used to calculate the parameters of the controller.

Bill of Materials

There is no definitive bill of materials for a Fabricatable Axis, as the parts and sheet stock required will vary depending on the dimensions set by the user. Table 1 shows the approximate cost of a single axis for a tabletop sized machine using parts specified in the repository.

Item	**qty**	**Cost**
Valchromat stock	1/2	$40
Screws and fasteners	30	$10
Closed Loop Stepper Motor NEMA23	1	$79.80
625 Bearings	12	$9.48
Eccentric Nut	6	$14.94
Total	-	**$154.44**

Table 1: Approximate bill of materials for a 1000mm Fabricatable Axis milled in Valchromat (MDF)

5 RESULTS

To assess the efficacy of the Fabricatable Machines designs, we have collected data on machines that were built over the course of the past three years. During that time, we have recorded thirty different machine designs being built, and the repository growing from a source of documentation to an online community. Besides the machine designs we recorded the build of, we know that other machines were also built but their results not documented in the repository. We estimate that there might be around one hundred machines in the wild.

Our methods for observation were either having guided conversations at the start of machine design, record design progress in the version control repository, and have an interview at the end of the machine design, or participant observation. Observation sessions lasted from several days to several weeks.

Machine Designs

From our thirty recorded machine designs, we have selected four machines we believe show a good representation of the results. They are described below and can be seen in Figure 5. Some other machines are shown in Figure 6. The open source repository was the main source of documentation for all machines. Machine builders used parametric designs, documentation, and tuning recommendations to design and fabricate new machines.

Machine 1: Wood CNC Milling Machine. This machine was built and implemented during a workshop at a fablab and makerspace conference that where held over five consecutive days. The participants were conference attendees, almost all of whom had experience running digital fabrication machines but not making them. We identify this group of users to be machine building novices. In groups of 3 or 4 they assembled The Fabricatable Axis using pre-cut parts, iterations of parts they cut on-site, and the repository documentation. The materials used were Valchromat and OSB. The participants successfully incorporated them into a single machine with a milling end-effector. The participants were taught a variety of machine-tuning exercises to increase the performance of such a machine. Once the machine was tuned, participants used the machine to mill wrenches out of steel. This group of users does not necessarily know or understand the different parameters that is driving the design of the Fabricatable Axis, or how they affect the implementation. They used the repository to interpret the engineering terminology, and the axis generator to visually explore and customize linear movement.

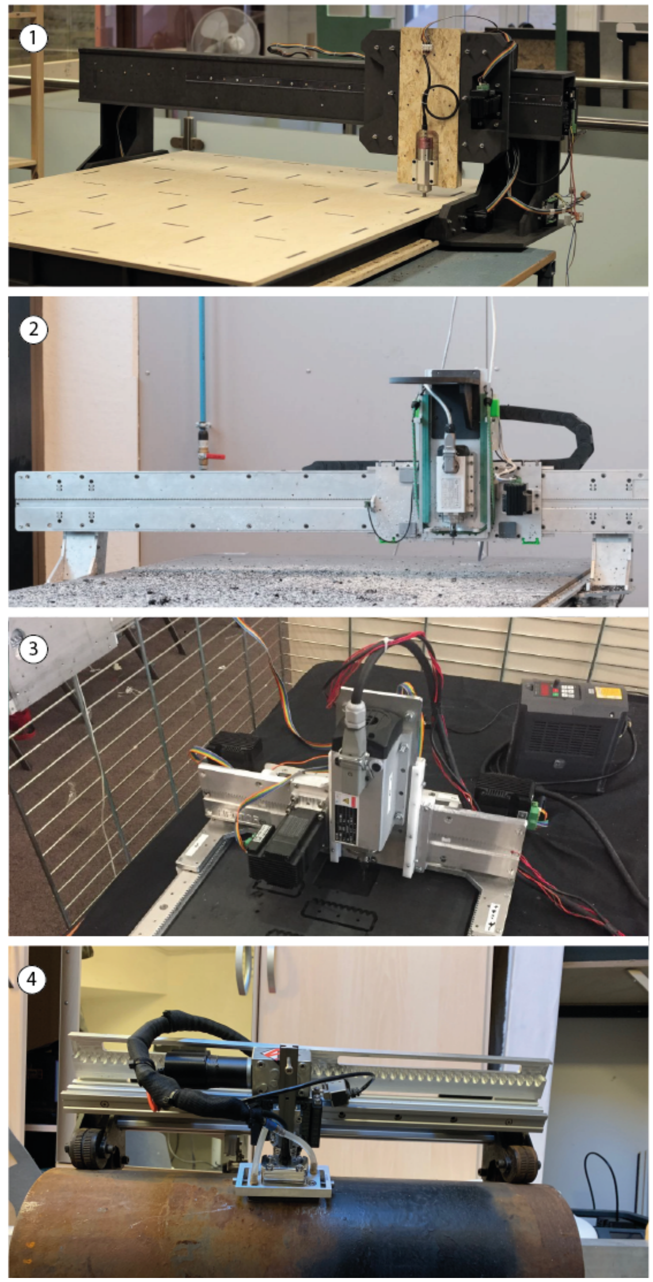

Figure 5: Machines 1 & 2 are two variations on milling machines. Machines 3 & 4 are nontraditional, where Machine 3 is a milling machine designed to fit into a suitcase and machine 4 semi-autonomous pipe inspection robot. All designs were built in makerspaces.

Machine 2: CNC Milling Machine for a Makerspace. A group of users had ample experience running a Makerspace, but were interested in adding a larger format mill. This group ranged from novice to knowledgeable in terms of machine building. They had experience running digital fabrication machines and some experience with maintenance for these machines. The participants first designed the work envelope of the machine they were aiming to create. They then generated the geometry for the axes they needed to fabricate in Grasshopper, and fabricated them out of aluminium at a user facility equipped with large-format CNC mills. To fly back home with their parts, they checked them in a ski bag as "sporting equipment". Once home, they assembled and wired up the machine using the online repository documentation and some remote technical support. The machine is now in use in the makerspace as their CNC mill and an important part of the makerspace infrastructure. These users where able to customize and manufacture all the parts required to make a machine. They encountered challenges with tuning and aligning the gantry design, but where able to overcome challenges by interacting with the repository. The implementation is now a part of the family of machines in the repository, and possible to download and manufacture.

Machine 3: Suitcase CNC Milling Machine. This was a machine building effort that took course over the course of several weeks. There was only one participant, and he had experience using Fabricatable Machines before starting the project. Using the source material from the repository, he designed, fabricated, and built a custom machine with his own design requirements (a mill that can fit in a suitcase). Because of mechanical issues and wiring complexities of previous machines, the participant made some modifications to his machine's design, including extending the glideblock surface area and implementing glideblock adjustment techniques. After evaluating their efficacy, he successfully submitted a pull request of his design modifications to the Fabricatable Machines repository.

Machine 4: Pipe Inspection Robot. This was a case where a startup needed to build a semi-autonomous robot for doing ultrasound inspection on welded pipes. We categorize the user as an knowledgeable machine builder. The Fabricatable Axis generator was used to make a linear actuator that moves a scanning device up and down in one direction. This was then attached to a platform with magnetic couplers that could be placed on the pipes that where to be inspected, and the axis was fitted with encoders to keep track of its position. Because of low torque requirements, the user set the gear ratio of the robot to be very high. This also makes it easier to fabricate because of its larger tooth diameter (the large tooth geometry can be seen in Figure 5, machine number 4).

6 DISCUSSION AND ANALYSIS

Observations

Customizing the Machine and Its Environment. In machine 3 and 4 we observe examples of users wanting to design their machine to fit specific environments. Machine 3 is designed to fit into a suitcase. Machine 4 is designed to be fitted and attached to a pipe. Also, in Figure 6, we see users fitting and attaching a milling machine on top of a car. In each of these examples, tailoring the machine to its environment is almost as important as the machine functionality itself. Our toolkit's capacity for custom workflows supports this user need.

CAD versus Real Life. During the workshops of machine 1, users were able to fabricate useful parts of the machine first, namely a single axis that is then used for constructing the machine. This allows them to reason spatially about the drive train composition of the machine with a tangible artifact. Conversely, machine 3 and 4 were made entirely in CAD before they were fabricated. This is because the more advanced users making machines 3 and 4 were able

Figure 6: Many different machines were built using the Fabricatable Machines Framework. On the top you can see a Geländewagen with a roof mounted CNC machine running on the car's battery power. In the middle and below is an upside down PCB mill for classroom instruction.

to already spatially reason about the drivetrain in a virtual digital environment. The interfaces of CAD tools can be quite intimidating for new users. However, our toolkit enabled both piecewise fabrication of machine parts which can be reasoned with physically (more suited to users with less machine design experience) as well as separating the digital and physical fabrication steps completely (more suited to users with advanced experience).

Tuning and Performance. Machine 2 initially had issues with a misaligned gantry. The users spent as much time optimizing and tuning the machine as they did assembling it. This is because they were not knowledgeable about what contributes to machine performance before embarking on the project. We observed that by interacting with a faulty machine, the users where able identify a problem, to adapt new knowledge about machine performance, and thereby improve the design. To them, the machine functioned as as a educational curriculum, in addition to being a means for fabrication. This may seem like we introduced a (possibly expensive) new failure mode for users who need machines. However, our experiences with novice users setting up off-the-shelf machines has been that similar issues with performance arise without the opportunity to learn more about how those issues relate to machine design.

Insights

Our experience designing the Fabricatable Machines and their documentation has led to several insights with respect to creating application-specific novel machines. Overall, our recommendation is to package the *common components* of machines together, as we did with the drive trains in the Fabricatable Machines project, to allow users to focus on their specific applications. This means that users can rely on the toolkit for the infrastructural needs of their machines, including drive train and motor control, while spending most of their time developing their own specific work flows. For example, for the pipe inspection machine, this allows the users to focus on the data collection head rather than the motion system.

We encapsulated machine building expertise in the Fabricatable Machines designs, so that the users did not necessarily need to have in-depth knowledge about pinion geometries or motion constraints, but could rely on the system to provide them with appropriate designs given force/speed criteria. However, another crucial insight we had was that we did need to provide the user with *scaffolding* into the system so that they could open that black box if they wanted to understand more.

We observed that users who make their own machine are likely to further customize and modify it throughout its life cycle. Typically we saw that machines were initially produced and tested using cheap materials like OSB or MDF. As a machine design solidified itself, users would simply replace parts with more robust materials like plastics or aluminium. It seems that the ability to manufacture and replace parts on the fly, gives machine designers a large esteem of confidence. We speculate that many of the more unique designs seen in the project seems to be a direct consequence of the rapid prototyping iterations and the quick turn around that our toolkit provides. This has led us to the insight that a machine does not only represent singular functionality (such as milling) but also may have *secondary requirements* (such as portability) which can be more easily met when the user is already customizing.

Tailored Machines

In summary, our insights from Fabricatable Machines include the need for common components, which was an initial design requirement, but also scaffolding users and enabling the addition of secondary requirements. As we create toolkits for more heterogenous user groups, allowing many points of entry for the user becomes crucial.

Lowering the threshold to tailor bespoke fabrication machines allows a new audience emerge in the field of fabrication. Through makerspaces, fablabs, and other institutions we are seeing that more and more people are seeking the means to harness the precision of computer controlled machines. Through this project we have seen that not only conventional machines were built, but newer and unexpected machines like multi-headed 3D printers, metal anodizing machines and, as shown in the last machine example, a pipe inspection robots. There is an interest not only in using digital fabrication machines and computer controlled machinery, but also in tailoring and customizing them. As the field of fabrication engages more diverse users, we need tools that reflect that diversity. We believe that the tools and methods presented in this paper fulfill an infrastructure role, like a software library that is used in many diverse applications.

7 CONCLUSION & FUTURE WORK

We presented Fabricatable Machines, an open-source toolkit for designing and creating bespoke computer controlled machines. The main feature of our toolkit is The Fabricatable Axis, a *resizable* and *fabricatable* linear axis that can be incorporated and assembled into machines. We have recorded a number of machines that were designed using our toolkit, showing how our contributions are aiding in making the machines. This paper stands as a flag in the ground for an ongoing project, and we are seeing a growing community using our toolkit to make new machines, downloading and extending existing machines and contributing to the online repository.

In particular, we are excited by the use of the toolkit for designing novel interactions and bespoke machine types. Digital fabrication, and digital interaction with material, has seen a significant increase in the field of HCI over the last decade. Our hope is that by lowering the threshold for creating and experimenting with fabrication machines, we are enabling HCI researchers to further investigate new workflows and novel types of fabrication tools.

As a result of our analysis, we believe that an important future contribution would be to shift the toolkit to a more user-driven tool. Rather then manipulating axis-per-axis parameters, and assembling the axes manually, the tool could be used to capture machine intent, and from this generate possible machine configurations. This would also present an opportunity to create on-the-fly dynamic control systems, where the control system controlling the machine is updated as the configuration and composition of axes are changed.

ACKNOWLEDGMENTS

The authors would like to thank Fellesverkstedet in Oslo for their continuous effort to promote open source hardware. We would also like to thank Alex Schaub and other fabricatable machine builders worldwide. Finally, we thank Jasper Tran O'Leary and Adrian Rutle for their help with this manuscript.

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