Unitless: Modeling and fabricating objects without measuring tools

Danny Leen, Marc Lambaerts

Danny Leen, KU Leuven – Fablab Genk
Genk, Belgium
Danny@fablabgenk.be

Marc Lambaerts, KU Leuven – Fablab Leuven
Leuven, Belgium
Marc.Lambaerts@kuleuven.be

Abstract

Digital fabrication allows users to fabricate objects without the need of measuring. However, designing digital 3D objects is generally done using callipers, rulers, protractors and other physical measurement tools. By translating physical dimensions to a digital design, it is possible that errors occur. Where traditional crafts, for example can make precise woodworking joinery by constantly checking and adjusting the progress of the joint, in a digital fabrication process it is not feasible to make adjustments during fabrication. Therefore, the designer needs to iterate over completed parts, this shifts the problem from making adjustments in the process (e.g. crafts) to making adjustments in the digital design. In this paper we describe two novel methods on how users can design and fabricate objects without measuring using digital fabrication. First, we present 'Strutmodeling', that allows users to design objects using struts that connect to magnetic hubs, allowing the user to build objects in physical space. The struts are automatically tracked in a digital environment where the object can be exported for digital fabrication. Secondly, we present a work in progress: 'Hand held fabrication', an end-to-end fabrication process that combines digital fabrication and hand-held tools. We constructed a digital environment to design woodworking joinery, that automatically generates custom jigs to allow users to fabricate the designed object using hand held tools without measuring.

Keywords

HCI, Digital fabrication, Design tools

1 Introduction

In traditional crafting techniques fabricating objects by hand is a very tactile process, the craftsman is in direct contact with the material throughout the entire fabrication process. In every step of the build it is possible to make fine adjustments to get the best result. In digital fabrication the machine translates computer generated instructions to the physical movement of a tool, therefore making fine adjustments to the object is not possible. When using digital fabrication, the experience of making an object shifts from the traditional crafts (hands on) experience to be a craftsman in the digital environment.

DOI: 10.5281/zenodo.1344532

Figure 28: Example of Strutmodeling and Hand-held Fabrication

While the fabrication is done by machines that mill, print and cut at sub-millimetre resolution, when designing in a digital environment most of the time, the process is still done the same as in traditional crafts. Designer need to operate and interpret different physical measurement tools (e.g callipers, rulers etc.) and translate the results into a digital environemt. Because these tools are not digitally connected, the designer needs to overcome the disconnect between the physical and digital environment. By doing this designers are prone to make errors [4], this problem is not new, researchers explored digital callipers, digital protractors [11] with the goal of digitising traditional measurement tools. In contrast this research focuses on finding ways to build objects without the need for measuring and still allow for fine adjustments during the fabrication process.

2 Contribution

This paper describes two novel interaction methods on how to build objects without measuring. The first method "Strutmodeling" is used as an input device see Figure 28 (Top), it is a modular toolkit for building objects using struts and magnetic hubs, it allows the user to physically build and fine-tune a model around existing objects. The position, orientation and length of every strut is electronically tracked allowing the digital environment to reproduce a 3D design. Further enhancements like convex hull, smoothing and exporting for digital fabrication can be done in the digital environment.

The second method: "Hand held fabrication" see Figure 28 (Bottom) is a work in progress that focuses on constraining hand-held tools with custom templates to fabricate objects designed in a digital environment. These custom templates are then made using digital fabrication (e.g. laser cutter and 3D printer) and constrain the movement of the hand-held tools in such a way that the only possible result is the object designed in the digital environment. This environment consists of an interface for generating woodworking joints (e.g. finger joints, dovetails) and it generates custom jigs for going from stock material to the designed object. These jigs constrain the tools in such a way that users can build the object without measuring in the fabrication process.

3 Strutmodeling

Strutmodeling is a modular low-cost toolkit using adjustable struts for physical modeling 3D objects. Physical 3D models of struts are immediately captured in software and result in readily available models for 3D printing or laser cutting. Our toolkit uses struts that are extensible, thus can cover a wide variation of lengths, and allows an arbitrary number of struts to be connected to a magnetic hub. Struts are self-contained and embed computational elements for both sensing and communicating their orientation, size, and topology information. Strutmodeling contributes to the democratization of 3D design and makes 3D designs more accessible and comprehensible by introducing 3D modeling activities in physical space. Our toolkit balances a high degree of freedom in design, cost-effectiveness and modularity which makes it specifically useful for the DIY maker community and sporadic users of digital fabrication. In addition, the embedded sensing capabilities allow struts to be used as measuring devices for lengths and angles and tune physical strut models according to existing physical objects.

3.1 Designing an ergonomic laptop stand

When designing a custom ergonomic laptop stand, not only the dimensions of the laptop is needed also the optimal angle and height of the laptop needs to be determined so that it is well aligned with the external monitor. Without Strutmodeling the designer would start out sketching and measuring all the lengths, angles and translate them into the preferred CAD environment. Where after the design can be 3D printed and tested, if the design needs adjustments the designer alters the digital design and start over the 3D printing process, in this case the iterations are done over fully 3D printed objects.

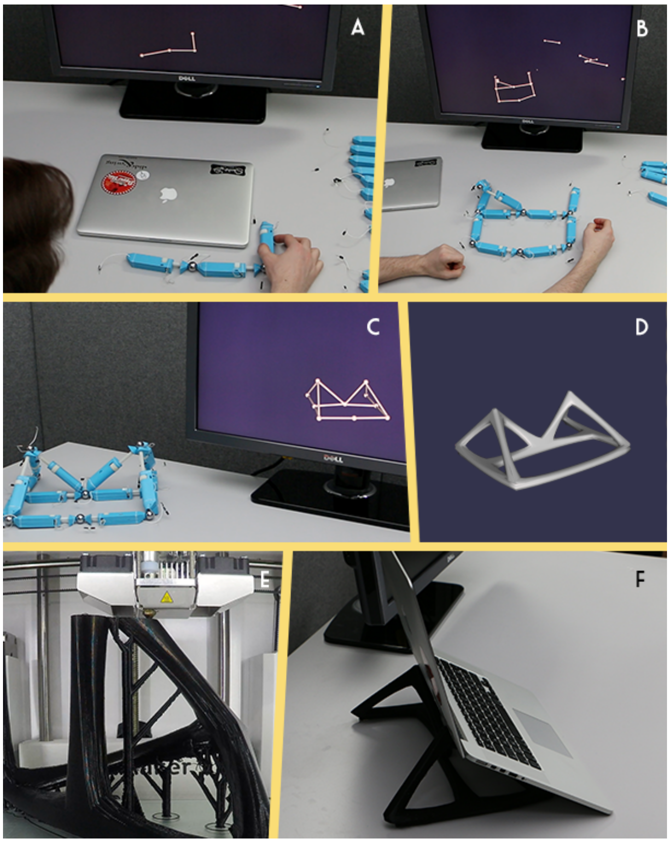


Figure 29. An ergonomic laptop stand modeled, tested, and adjusted with Strutmodeling.

With Strutmodeling the designer can start by connecting the magnetic hubs to the struts, see Figure 29. Adjusting the length of every strut to match the dimensions of the laptop (a). To make the correct angle of the laptop the struts can be placed in any 3D orientation (b), once finished building the Strutmodel, the laptop can be set on top of the Strutmodel allowing the designer to check and make fine adjustment to the Strutmodel, so it matches the height of the external monitor exactly. All the struts are tracked in real time by the digital environment (c) and when the design is finished, the Strutmodeling rendering environment converts the Strutmodel to a 3D printable design by automatically applying post-processing steps (d). The final design is ergonomically sound from the first 3D printing iteration (f).

3.2 Related work

Strutmodeling draws from and builds upon prior advances in end-user 3D modeling software, construction toolkits to accelerate the fabrication and design process.

3.2.1 Construction and modeling toolkits

Closest to our work, a number of projects construction kits have a hub and strut layout. FlexM [1] proposes a kit consisting of hubs with three adjustable anchor points. To capture the topology, the work proposes and explores implementations in which hubs communicate by transmitting light signals through struts and the angle between struts is measured using potentiometers. Building on top of these concepts, Posey [12] is a tangible modeling kit that senses the topology as well as orientation of struts using infrared LEDs and sensors in every hub. Jacobson et al. [3] present a construction kit that uses a hall effect sensor to track the rotation of joints and communicates states through an embedded bus system. As hubs have a limited number of anchor points and require a minimum of 90 degrees between their angles, the kit is particularly suitable for modeling and animating skeletons. Glauser et al. [2] further optimized the design to eliminate gimbal lock effects. To allow for designing more organic forms, the Senspectra tool [5] uses malleable struts that bend in any direction. Bend angle are estimated by analysing the reflectance of IR light transmitted through struts. Gluss [7] and Topobo [6] present similar construction kits but focus on rendering and animating forms in the physical world using actuators instead of digital modeling. Our work is different in that hubs do not have a fixed number of anchor points and allow for small angles between adjacent struts. As such, Strutmodeling is optimized for modeling detailed outer-surface of objects that are ready for fabrication. In contrast, previous approaches target skeleton modeling and focus on learning and play [12] or animation [2].

As such, Strutmodeling is better suited to design the outer surface of 3D models, often times requiring many struts, instead of the inner skeletons, which is sparser. Additionally, adjusting the length of struts allows for realizing objects of arbitrary sizes and complexities.

3.3 System overview

Strutmodeling consists of an adjustable strut design and universal magnetic hubs that connect to struts in any arbitrary configuration. The struts we created are extensible and embed hardware for both sensing and communicating their orientation, size, and topology information.

Tracking a precise absolute position not feasible without external tracking systems, our approach realizes accurate digital reconstructions by combining the orientation data of all struts with topology information, describing which struts are connected together. Unlike hubs with fixed anchor points, magnetic hubs snap to struts in any configuration. On the flipside however, connected struts only have a single electrical connection point which makes it impossible to power the system as well as transmit the orientation, length and topology information. Every strut is self-powered via an internal battery and communicates wireless to a digital environment. By transmitting the data from all struts to a digital environment it renders a digital representation of the physical Strutmodel.

3.3.1 Hardware design

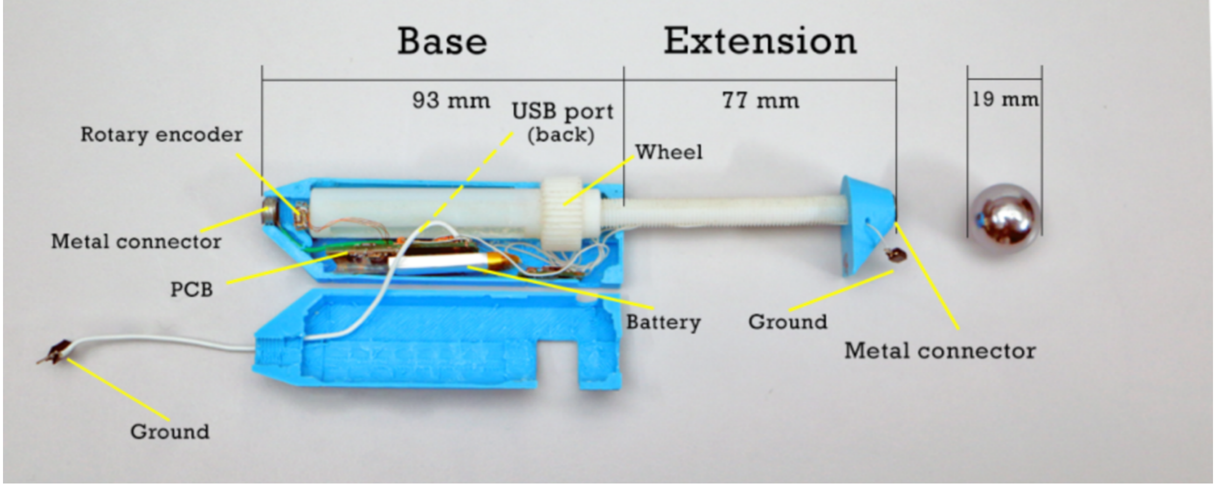


Figure 30. Internal components of a strut

Every strut consists of a custom printed circuit board (PCB) that tracks its orientation, this is partly done by using an inertial measurement unit (IMU). This IMU consists of an accelerometer, gyroscope and magnetometer, this tracks the absolute orientation in 3 dimensions. To further enhance the orientation the struts tracks the topology of all connections, allowing it to refine the position of every individual strut. To get the orientation data from the strut it uses an ARM Cortex M0+ microcontroller embedded in the Bosch BNO055 integrated circuit, which packs 3 different sensors: a triaxial 16-bit gyroscope, a triaxial 14-bit accelerometer, and a geomagnetic sensor, of which the latter one is disabled. To track the length of a strut the PCB integrates a miniaturized rotary encoder, it outputs 12 pulses per revolution. the pitch of the thread in the struts is 1mm. This result in 12 pulses per mm allowing for accurate length detection of each strut. All this data needs to be communicated to the digital environment, each strut is fitted with a nRF24L01+. This 2.4GHz radio transceiver protocol allows up to 780 struts in a single mesh network. The fusing of the positioning data is done in the ARM M0+ microcontroller, the detecting of adjacent struts, formatting data and communicating to the nRF24 module is done by an ATMEGA 328P. All this is powered by a 130 mAh LiPo battery. Detecting neighbouring struts is done by sending a signal to the magnetic hub and letting the rest of the struts listen to this signal and report back that they found a voltage. Then the process is repeated until all struts have responded. This allows the digital environment to reconstruct the full topology of the Strutmodel. As our mesh network has a bandwidth of 2Mbit, reconstructing the topology of 20 struts takes less than one second. The total cost of all electronic components is around 16 euro.

3.4 Strutmodeling as input modality

Strutmodeling allows designers to make fine adjustments in the design process, enabling them to adjust models early in the process. Just like the traditional crafts where adjustments can be done during the fabrication process, Strutmodeling shifts making adjustments to the design phase. By using Strutmodeling designers can accelerates the process by not iterating over 3D printed objects but designing in situ and adjusting early on in the process.

Although Strutmodeling uses a novel way of designing for digital fabrication. We notice some limitations that are important to discuss. First, features smaller than a single strut cannot be modeled, we think there are two solutions to this problem, further miniaturization of the PCB and the physical struts or the designer also can build the Strutmodel in a bigger scale and scale it back down in the digital environment, by doing this the designer sacrifices many of the beneficial properties of Strutmodeling. Lastly, designing big objects a lot of struts are needed, to overcome this we think further research has to be done exploring telescopic mechanisms allowing the strut to extend multiple times farther then its own body length.

4 Hand held digital fabrication

Hand held fabrication focusses on generating custom jigs for multiple hand-held tools. It allows designer to start with a stock of wooden panels and end up with the object that was designed in the digital environment. The idea of using tools to make jigs, to make an object is not new. When searching in online repositories like Thingiverse we can see designers utilizing 3D printers and laser cutters for making templates, jigs or fixtures. Using these sub-millimetre precision digital machines to fabricate these objects make it easy for designers to build objects with closer tolerances than doing it by hand. Oftentimes these tools are replicas or adaptations of existing traditional jigs that are used in specific subsection of the making process.

Hand held fabrication integrates generating custom jigs into the design- and making- process. It allows the users to start from stock material to end up with a physical model, therefore Hand-held fabrication is an end-to-end digital environment for woodworking with hand held power tools. This is done by generating custom jigs that are made using digital fabrication tools. The hand-held tools are constrained in such a way that the only possible result is the object designed in the digital environment. Utilizing the precision of digital fabrication and still having the benefits of the more traditional fabrication process. It allows users to fabricate objects using jigs and checking the progress in every step towards the completion of the object.

4.1 Process example

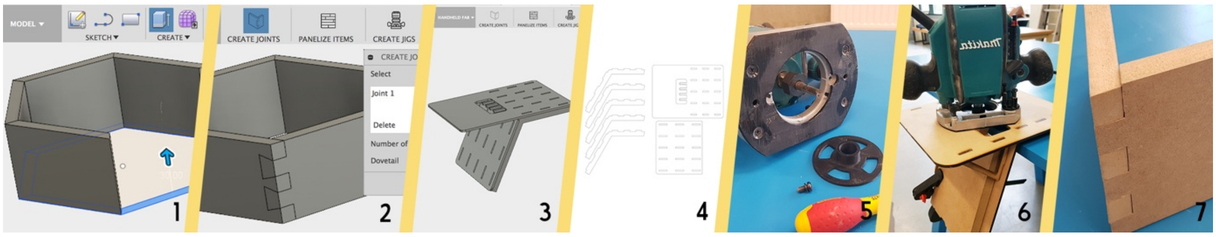


Figure 31. Example process: 1. designing the object, 2. generating the joint, 3. generated jig, 4. plans for laser cutter 5. installing router copy ring 6. milling the part 7. finished part

When designing a woodworking finger joint the designer starts by (Figure 31): 1. modeling the object in a traditional CAD software environment. 2. The designer then selects the hand-held environment and select the edges to apply the finger joint to. 3 Once done cutting out all the parts, the users can select the "generate jigs" button to compute the needed dovetail jigs. 4. This will also generate all the needed vector files and a 3D representation of the jig. 5. than the user needs to install a copy ring in the router 6. The user traces the profile of the jig 7. resulting in the joint that can be test fitted and glued.

The user can click the panelize button that lays all objects on the stock material and generates the cutting plan (Figure 33). It will also generate the needed puzzle pieces (Figure 34. 1. connector piece 2. universal puzzle piece 3. edge constraining puzzle piece to constrain the circular saw Figure 34. 1. connector piece 2. universal puzzle piece 3. edge constraining puzzle piece allowing the stock material to be cut to size. Once all the pieces are cut to size, the user needs to assemble the jig see Figure 35 that constrains the router and mount the copy ring (Figure 36) in the router. Once this is done the user needs to clamp the workpiece in the jig and trace the toolpath with the router. When fabricating a specific part of the object the user can check the fit or size compared to other parts.

4.2 Related Work

Hand held fabrication draws from and builds upon prior advances in end-user 3D modeling software, digital fabrication tools and techniques to accelerate the design and fabrication process. Shaper [8] allows users to make objects with an actuated hand-held router, provided with a screen the user can select a desired shape to cut. It then can actuate the hand-held router to help align the user to cut a specific shape. When the user deviates from the cutting path Shaper has a limited amount of actuation to compensate and cut out the shape according to the dimensions specified earlier. FreeD [14] uses a hand held Dremel like tool that allows users to sculpt an object in 3D, by retracting the mill bit and stop spinning the user cannot cut beyond the desired shape. Although these tools are very useful tool build objects, not all actions are ideal to be cut with a router, for example cutting out flat stock material is better done on a circular saw. With hand held fabrication the right tool is constrained for the right cut and no actuation of the tools is needed. Drill sergeant [9] augments hand held tool with a real-time digital layer, it can communicate additional information for example: depth of drilling, orientation or safety instructions. Matchsticks [10] builds upon the same idea and shows a purpose build CNC machine that parametrises different woodworking joints. The user is given the option to select what they want to build via a touchscreen connected to the CNC machine and guides the user through the process of building the object. Purpose build CNC machines are good at what they are intended to do but are hard to come by or build by novice makers. In contrast, hand held tools are readily available for makers and combining them with our digital Hand-held fabrication environment allows them to make complex woodworking joinery using simple generated jigs.

4.3 Software environment

The software environment (as a work in progress) supports generating two types of woodworking joints: finger joints and dovetails. Making complex geometries and joints can be very challenging, craftsmen use universal templates and jigs to ease the process of fabricating these woodworking joints. Setting up these universal jigs requires lot of experience and can be difficult for novice makers.

Hand held fabrication mitigates this problem by generating jigs with custom toolpaths in a 3D software environment. The designer can select two faces (in any orientation) that share an outer edge, the software automatically generates the joint using the defined parameters (e.g. amount, shape, angle). Once the user is done designing the 3D model, the software generates all cutting plans and the jigs needed to fabricate the object by hand.

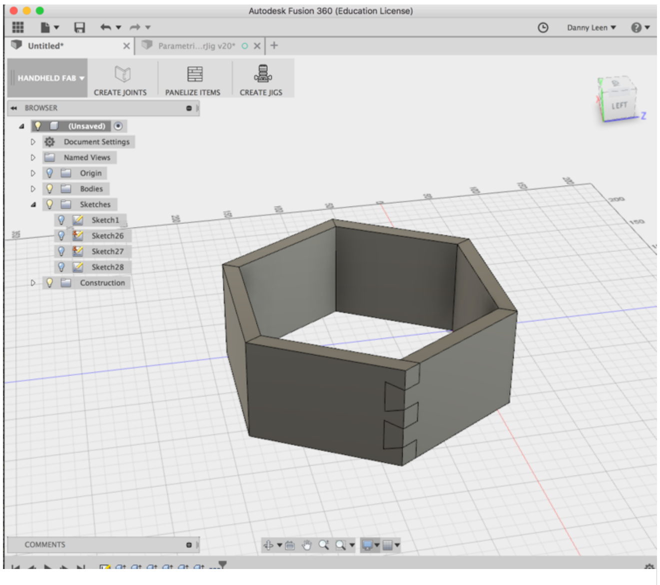


Figure 32. Digital hand-held fabrication design environment

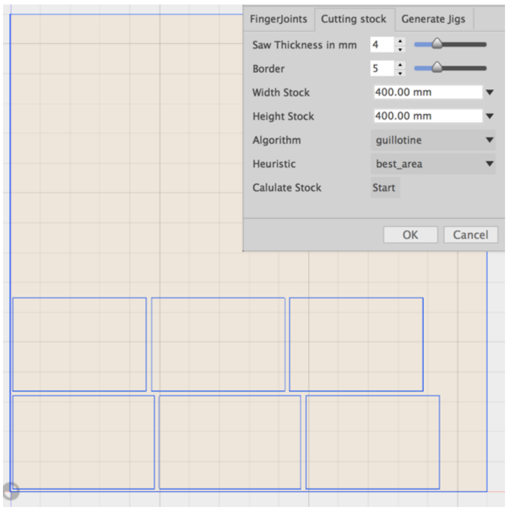
Our work utilizes Autodesk Fusion 360 as a rendering environment and keeps al the traditional CAD operations when designing objects. In addition, we build a custom layer on top of Fusion 360 with the Hand-held fabrication user interface that allow different actions to be performed. Currently the software consists out of three actions, 1. the generation of woodworking joints 2. the panelize function 3. generating jigs and toolpaths for a handheld router and circular saw.

4.3.1 Woodworking joint geometry generation

When making angled woodworking joints manually, a lot of calculations need to be done by the users. This math can be challenging and difficult for novices. By embedding these calculations into a digital environment, we can compute different types of joints in seconds. This allows the user to generate different joint types that normally are hard to calculate manually. The joint generation algorithm is developed in such a way that the designer can apply the joint on every convex body with two flat faces that share one edge. For now, only dovetails and finger joints are implemented, but with little alteration of the code many more (decorative) joints can be generated.

4.3.2 Panelize function

As hand held fabrication is an end-to-end environment, it starts from the stock material and lays out all parts needed for the designed object. Designers can input the material stock that is present in the shop and generate a custom cut plan for the hand held circular saw. When using a hand-held saw, the user always needs to cut farther then the size of the workpiece. This is because the blade on a circular saw is round and when cutting out a profile it has to generally cut half the blade's diameter farther. In Hand held fabrication the software constrains the user to allow them to make only straight cuts throughout the stock plate. This problem can be defined as the "guillotine cutting problem" [13], to solve this we use a specific form of binpacking algorithm called the greedy approximation algorithm. The user than can select different packing heuristics to make the best use of the stock material that is available. Currently we are also implementing how puzzle pieces can be used to get the saw to cut in the right place. Using all custom puzzle pieces will be to inefficient, so making reusable lengths and making a custom final piece allows the user to get the right length see Figure 34.



Saw Thickness in mm 4
Border 5
Width Stock 400.00 mm
Height Stock 400.00 mm
Algorithm guillotine
Heuristic best_area
Calulate Stock Start

Figure 33. Guillotine cut panelize function

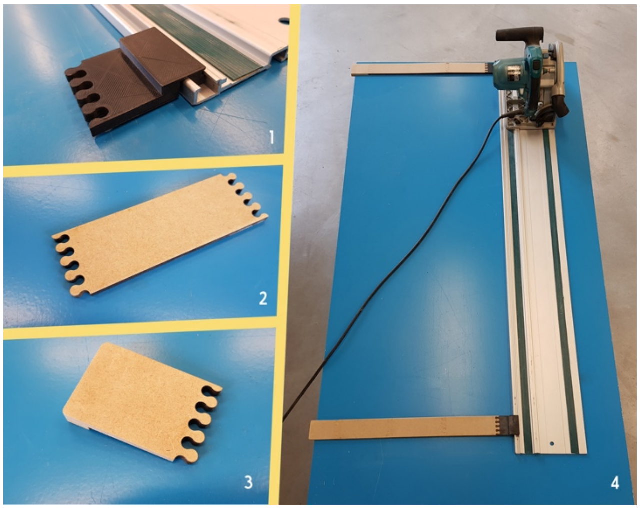


Figure 34. 1. connector piece 2. universal puzzle piece 3. edge constraining puzzle piece

4.3.3 Jig generation

To constrain the hand-held tools the software generates toolpaths that physically constrain them, an example of such a jig can be seen in Figure 35. The router is equipped with a 3D printed copy ring (Figure 36) that follows the generated profile of the toolpath. This ring can be 3D printed or the standard copy ring of the router can be used. Generating the toolpaths takes into account the router bit diameter and the copy ring diameter. These parameters are accessible for users to be adjusted according to the needs of the workpiece. The jig itself is a fully parametrised model allowing it to be customized by automatically altering the parameters in the digital environment. By not using code to generate the jigs the expert user can tweak or add parameters to the model to get custom behaviour.

Figure 35. Jig for cutting a finger joint

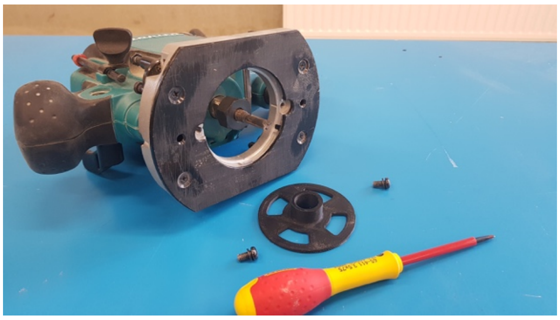


Figure 36. 3D printed router copy ring

4.4 Future implementation

As this project is a work in progress the process for making an object needs some development. In the first place the digital environment needs to support angled cuts using the miter saw. Preliminary tests are done with constraining the angles of the machine see Figure 38 and Figure 37.

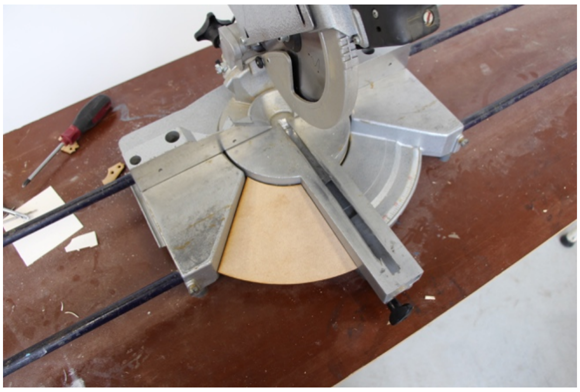


Figure 38. Constraining prototype first angle

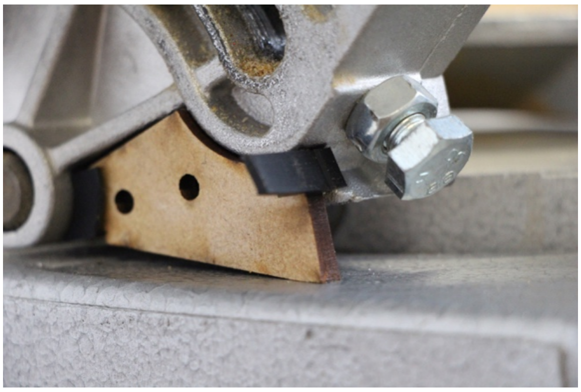


Figure 37. Constraining prototype second angle

Further, adding constrains to a hand-held drill will be useful to make dowel joints, providing the user with the ability to use modern construction techniques (e.g. 32 mm system). Also, the documentation for assembling the jigs and performing cuts also need to be generated. It would be useful for the digital environment to give feedback on the rigidity of the joint construction, on sizes of mills and copy ring that can be used, we will investigate this further. More research can be done in different kinds of material optimization, for example reusing jigs for different joints and already aligning the angled cuts on the panelize function. We think all these optimizations will increase the performance of the system.

4.5 Hand held fabrication as output modality

Hand held fabrication uses digital fabrication to constrain tools that are operated by hand in a novel way. By making the jigs with digital fabrication it utilizes the sub-millimetre accuracy of these machines.

Therefore, the user can translate the same accuracy to the hand-held tools when making objects. By allowing the users to make all parts individually they can test for size and fit in the fabrication process. This allows them to intervene in the process of making, where in digital fabrication the testing is done when the object is already milled, printed or laser cut. By being able to make fine adjustments to the model the users can get for example a better fitting joint. By making the model in a digital environment all the sizes of the object are present and making toolpaths and jigs can be fully automated. When the user laser cuts the jigs all these measurement will be materialized into physical objects.

5 Conclusion

In this paper we presented two tools that explore new methods on how users can make objects using digital fabrication. For input we developed Strutmodeling allowing users to model with struts and hubs around existing objects. As an output tool we are working on Hand held fabrication, allowing users to build objects using woodworking joints and constrained hand-held tools. With constraining jigs that benefit from the sub-millimetre precision of digital fabrication machines. By building with hand held tools it allows users the have more control over the process, allowing them to make better objects.

To have a true Unitless method of making objects, first a novel input modality is needed that has no need for manually translating measurements into a digital environment. Secondly, a novel output method is needed that allows for objects to be fabricated without measuring. With Strutmodeling as an input method and Hand-held fabrication as an output method we think that combining these will provide an unitless fabrication method.

References

1. Markus Eng, Ken Camarata, Ellen Yi-Luen Do, and Mark D Gross. 2006. Flexm: Designing a physical construction kit for 3d modeling. International Journal of Architectural Computing 4, 2 (2006), 27–47.
2. Oliver Glauser, Benedek Vartok, Wan-Chun Ma, Daniele Panozzo, Alec Jacobson, Cédric Pradalier, Otmar Hilliges, and Olga Sorkine-Hornung. 2017. Rig Animation with a Tangible and Modular Input Device. interactions 24, 2 (Feb. 2017), 16–17. DOI: http://dx.doi.org/10.1145/3041959
3. Alec Jacobson, Daniele Panozzo, Oliver Glauser, Cédric Pradalier, Otmar Hilliges, and Olga Sorkine-Hornung. 2014. Tangible and Modular Input Device for Character Articulation. In ACM SIGGRAPH 2014 Emerging Technologies (SIGGRAPH '14). ACM, New York, NY, USA, Article 24, 1 pages. DOI: http://dx.doi.org/10.1145/2614066.2614072
4. Jeeeun Kim, Anhong Guo, Tom Yeh, Scott E. Hudson, and Jennifer Mankoff. 2017. Understanding Uncertainty in Measurement and Accommodating Its Impact in 3D Modeling and Printing. In Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17). ACM, 1067–1078. DOI: http://dx.doi.org/10.1145/3064663.3064690
5. Vincent LeClerc, Amanda Parkes, and Hiroshi Ishii. 2007. Senspectra: A Computationally Augmented Physical Modeling Toolkit for Sensing and Visualization of Structural Strain. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07). ACM, New York, NY, USA, 801–804. DOI: http://dx.doi.org/10.1145/1240624.1240744
6. Hayes Solos Raffle, Amanda J. Parkes, and Hiroshi Ishii. 2004. Topobo: A Constructive Assembly System with Kinetic Memory. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04). ACM, New York, NY, USA, 647–654. DOI: http://dx.doi.org/10.1145/985692.985774
7. Robert L. Read. 2016. The Gluss Project. Article. (16 September 2016). Retrieved March 27, 2016 from https://hackaday.io/project/13277-the-gluss-project.
8. Alec Rivers, Ilan E. Moyer, and Frédo Durand. 2012. Position-correcting Tools for 2D Digital Fabrication. ACM Trans. Graph. 31, 4, Article 88 (July 2012), 7 pages. DOI: http://dx.doi.org/10.1145/2185520.2185584
9. Eldon Schoop, Michelle Nguyen, Daniel Lim, Valkyrie Savage, Sean Follmer, and Björn Hartmann. 2016. Drill Sergeant: Supporting Physical Construction Projects Through an Ecosystem of Augmented Tools. In Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16). ACM, New York, NY, USA, 1607–1614. DOI: http://dx.doi.org/10.1145/2851581.2892429
10. Rundong Tian, Sarah Sterman, Ethan Chiou, Jeremy Warner, and Eric Paulos. 2018. MatchSticks: Woodworking Through Improvisational Digital Fabrication. In Proceedings of the 2018 CHI Conference on Human Factors in

Computing Systems (CHI ’18). ACM, New York, NY, USA, Article 149, 12 pages. DOI: http://dx.doi.org/10.1145/3173574.3173723

11. Christian Weichel, Jason Alexander, Abhijit Karnik, and Hans Gellersen. 2015. SPATA: Spatio-Tangible Tools for Fabrication-Aware Design. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’15). ACM, New York, NY, USA, 189–196. DOI: http://dx.doi.org/10.1145/2677199.2680576
12. Michael Philetus Weller, Ellen Yi-Luen Do, and Mark DGross. 2008. Posey: Instrumenting a Poseable Hub and Strut Construction Toy. In Proceedings of the 2Nd International Conference on Tangible and Embedded Interaction (TEI ’08). ACM, New York, NY, USA, 39–46. DOI: http://dx.doi.org/10.1145/1347390.1347402
13. Amit Zoran and Joseph A. Paradiso. 2013. FreeD: A Freehand Digital Sculpting Tool. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’13). ACM, New York, NY, USA,2613–2616. DOI: http://dx.doi.org/10.1145/2470654.2481361