

FreeD – A Freehand Digital Sculpting Tool

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ABSTRACT

In this paper, we present an approach to combining digital fabrication and craft, emphasizing the user experience. While many researchers strive to enable makers to design and produce 3D objects, our research seeks to present a new fabrication approach to make unique, one-of-a-kind artifacts. To that end, we developed the FreeD, a hand-held digital milling device. The system is guided and monitored by a computer while preserving the maker's freedom to sculpt and carve, and to manipulate the work in many creative ways. Relying on a predesigned 3D model, the computer gets into action only when the milling bit risks the object's integrity, by slowing down the spindle's speed or by drawing back the shaft, while the rest of the time it allows complete gestural freedom. We describe the key concepts of our work and its motivation, present the FreeD's architecture and technology, and discuss two projects made with the tool.

Author Keywords

Computer-Aided Design (CAD); Craft; Digital Fabrication; Carving; Milling.

ACM Classification Keywords

H.5.2 [Information interfaces and presentation]: User Interfaces.

INTRODUCTION

Over the last several years, digital fabrication technologies have altered many disciplines [4]. Today's designers can easily create, download, or modify a Computer-Aided Design (CAD) model of their desired object, and fabricate it directly using a digital process. In developing new manufacturing technologies, engineers seek an optimal solution, reducing the process to as few parameters as possible, and separating design from fabrication. Ease of use, accessibility, proliferation and efficacy grow as technology matures. However, qualities such as creative engagement in the experience itself are lost. The nature of interaction with the fabricated artifact is rarely the focus of new developments.

While the process of engineering minimizes risks, seeks efficiency, and enables automation and repetition, craft is

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about involvement and engagement, uniqueness of the final products, and authenticity of the experience [7]. Engaging in an intimate fabrication process and enjoying the experience of shaping raw material are inherent values of traditional craft. As a result of this engagement, handcrafted products are unique and carry personal narratives [10].

Our research interest lies in the cross-section between digital fabrication and the study of the craft experience. We wish to allow designers to engage with the physical material, not only the CAD environment. We hope to encourage the exploration of an intimate digital fabrication approach, introducing craft qualities into the digital domain. Our contribution is a system merging qualities of both traditions: minimizing fabrication risk by using a small degree of digital control and automation while allowing authentic engagement with raw material to achieve unique results.

The *FreeD* is a freehand digitally controlled milling device (Figure 1). With the FreeD we harness CAD abilities in 3D design while keeping the user involved in the milling process. A computer monitors this 3D location-aware tool while preserving the maker's gestural freedom. The computer intervenes only when the milling bit approaches the 3D model. In such a case, it will either slow down the spindle, or draw back the shaft; the rest of the time it allows the user to freely shape the work. Our hope is to substantiate the importance of engaging in a discourse that posits a new hybrid territory for investigation and discovery - a territory of artifacts produced by both machine and man.

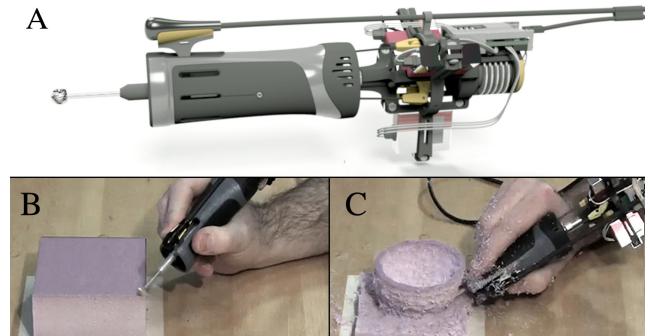


Figure 1: (A) The FreeD and (B-C) the process of making a bowl from polyethylene foam.

RELATED WORK

There is a rich history of HCI researchers exploring the domain of creativity using motion tracking and gestural inputs. Several projects studied the 2D creative domain of painting and sketching [1, 3, 5], and others enable 3D crea-

tive outputs – from 3D CAD output [11], to the control of the fabrication of 3D objects. Willis et al. developed several devices that use real-time inputs to construct physical forms [12]. Olwal et al. combined a computer graphics interface with physical objects, working with an industrial lathe [8]. Rivers et al. developed a position-correcting 2D router tool, achieving accurate cuts on large-scale surfaces, while allowing the free guiding of the tool [9]. A similar 3D concept is the Precision Freehand Sculptor (PFS), a compact, handheld tool that assists surgeons in accurate bone-cutting tasks [4]. The computer retracts the tool's rotary blade, based on data from an optical tracking camera, and ensures high accuracy. These last two projects allow accurate results, but they do not explore the domain of a free-form 3D fabrication, and instead focus on aligning the device cutting head to a pre-design tool path.

The *Haptic Intelligentsia* is a 3D printing device using a robotic arm and an extruding gun. The user freely moves the gun, receiving real-time haptic feedback. When the tip of the gun is moved into the volume of the virtual object, the arm generates resistance, allowing the user to feel the object [6]. While applying an additive approach, the *Haptic Intelligentsia* shares similarities with our device. However, the FreeD frees the user from obstacles and limitations inherent in the use of a robotic arm, fulfilling a freeform handheld device, a major interactive quality in our work.

DIGITAL PRACTICE AND TRADITIONAL CARVING

Prior to developing the FreeD, we investigated a range of carving practices. For several years we worked closely with a traditional violinmaker who uses only hand-tools in his process. Last year we began ethnographic work with several African wood artists (mostly Makonde carvers and Bushmen artists). This study helped in defining the interactive philosophy of the FreeD, by outlining the craft qualities we would like to impart to the digital fabrication environment. We designed the FreeD to allow complete gestural freedom - similar to working with a chisel or a knife - and to allow an intimate tangible experience with a raw material. Nevertheless, the FreeD also gives the user a “safety net” by relying on a pre-designed CAD model, similar to working with a digital machine.

Unlike the woodcarver, a digital designer has access to a rich digital history, and can both monitor and control the design process. A digital design file specifies exactly what a machine should produce. This fabrication process doesn't depend on the skills and involvement of a human maker. Typically, the job of the designer is finished before the fabrication process starts, while the wood carver invests the majority of effort in the making process itself.

Let us examine this making process more closely. The violinmaker relies on well-known references, mostly old designs of important makers, executing a plan that was selected beforehand. He uses drawings, photographs, and calipers to guarantee the perfection of the product. Similar to a designer who uses a 3D printer to precisely fabricate a

model, the violinmaker relies on previously tested designs. However, unlike digital practice, in craft the maker is constantly putting the work at risk of being damaged. More than that, despite sharing similar designs, violins differ from each other through the qualities of the material and work: the detailed design interpretations of the makers.

The FreeD integrates some aspects similar to the violin-making process into the digital practice. A predefined model serves as a guideline, removing the inherent risk of handcraft (guaranteeing the user doesn't damage the design). However, the FreeD lets the user reinterpret the pre-designed model by making on-the-spot creative decisions.

In traditional practice, carvers use a variety of methods when removing materials from a raw block. When arching the violin's plates, for example, the violinmaker uses an organized procedure. He attaches the wood to a workbench, removing wood with chisels and gouges in consistent patterns from one side of the block to the other. On the other hand, the African artisans we visited never relied on graphic references and instead visualize the design solely in their minds. While carving, they can change the working procedure during the process, switching carving directions or even designs intuitively.

With the FreeD, the raw material is bound to a table – similar to violinmaking - and is not held by hand. We allow the maker to choose the method of operation, developing a personal approach to the process. The maker can use an organized procedure (like the violinmaker), a more intuitive one (like the African artist), or a mix of both. This expressive method of operation will influence the quality of the final artifact. Our major contribution is giving the designer direct engagement with the material, allowing her to create a unique signature: structural, chaotic, or both, making decisions that were made during the work. Together with the freedom of interpretation mentioned previously, the FreeD re-introduces some of the craft values into digital fabrication. Moreover, the FreeD can be used as a learning tool, helping makers in their first sculpting steps.

FREE D OPERATION AND INTERACTION

To operate the FreeD, the user sits in front of the material, which is attached to a wooden table (Figure 2A). He is free to investigate any milling approach, such as extruding lines, drilling holes, trimming surfaces, or using an arbitrary pattern. The computer automatically compensates for any mistakes, applying a “protection field” around the object, with minimal interference to the process. The computer will intervene only when the virtual tracking of the milling bit approaches the surface of the virtual 3D model.

While milling, the FreeD responds to the users' actions when these actions put the model at risk. These responses, whether they are changes in the spindle speed or movements of the shaft, inform the user of the relative location of the bit with respect to the surface of the model. Together with the PC's screen, this information supports the user in both learning and controlling the shape he is fabricating.

The screen can be used as a visual reference to the virtual model. On the screen, where the CAD model is presented, a virtual mark represents the current position of the FreeD's milling bit. If she wishes, the user can rely on this mark during the work, especially in the initial stage where the virtual shape is not yet revealed in the raw material.

THE SYSTEM'S ARCHITECTURE & IMPLEMENTATION

Most of the computation is done on a PC with 4GB memory, with double 3.2GHz Intel Xeon CPUs. We use a magnetic motion tracking system (MMTS), which has no drift nor requires an optical line-of-sight. We chose the Polhemus FASTRAK system, an AC 6D system that has low latency (4ms), high static accuracy (position 0.76mm / orientation 0.15° RMS), and high refresh rate (120Hz).

The FreeD Hardware Design

The tool contains a custom milling mechanism (spindle) built on top of a long shaft (Figure 2B) connected to a DC motor (FAULHABER Coreless 1727..C with up to 7800 RPM with no load, and up to 5mNm torque). The shaft and the 8mm round milling bit are made from steel. A 3D printed linear bearing is located underneath the handle. The shaft can be moved back and forth to provide linear control of the location of the milling bit with a dynamic range of 21mm. Three servomotors determine the shaft's position. The servos are perpendicularly aligned to the shaft. We chose MKS 6125 mini servos, which are strong (up to 5.8 kg-cm for 6V), small, and lightweight (25.26g).

An electronic circuit on the PCB communicates with the main computer via Bluetooth to control both the shaft movement and the spindle speed. It has an ATmega328 microprocessor and a TB6612FNG motor driver, and is powered with 5V and 12V power signals.

Data Flow and Control Software

On the computer, where the planned virtual model resides, the software is run in Grasshopper (a plug-in for Rhino). The software's input is the 6D location and orientation of the tool (via serial communication), and the outputs are commands to the control PCB on the FreeD. The communication with the PCB is one-sided synchronous, using virtual serial communication over Bluetooth (Figure 2C).

A zero order prediction of the next 3D position (projecting the previous step as the next one) is based on the current and last locations. The software calculates the distances to the CAD model from both the current location and the predicted one, and estimates which of the points put the model at higher risk. The spindle's speed is a function of the distance from the model. If it is farther than 10cm the spindle is off. Getting closer, the spindle operates at maximal speed, ready to mill material. If the bit is approaching the model surface (getting within 5mm range), it will slowdown to half speed on the surface as a linear function of the distance. This minimizes the chance of a crucial mistake, forcing slow work near the surface of the object. Any prediction of the bit getting into the model results in a command to shutdown the spindle's rotation.

The shaft control takes into consideration the tool's attack angle (the angle between the shaft and the normal to the model's surface at the closest point). The default shaft position is fully "open" ahead, with a 21mm potential to absorb the offset and step back. The software tries to minimize the chances of the bit entering the volume of the model, drawing it back as much as possible when detecting a risk. When the bit moves farther from the surface, the software will push the shaft back to its original position.

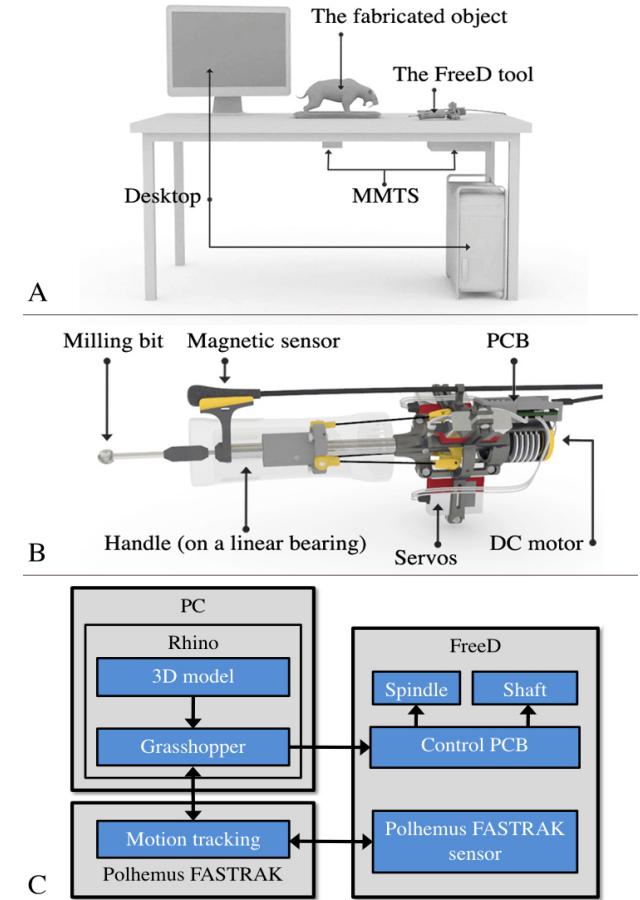


Figure 2: (A) The FreeD's environment, (B) the FreeD design, and (C) the system's data flow.

DISCUSSION

The FreeD was tested by two projects, both milled in polyethylene foam: a bowl (8cm X 5cm, Figure 1), and a saber-tooth tiger (24cm X 13cm X 8cm, Figure 3). With the current design we were able to mill foams and soft woods (balsa), although the later was significantly slower. We designed the CAD model of the bowl in Rhino, and purchased the model of the tiger online. The process of fabricating the bowl took us 30 minutes to complete (removing around 120 cubic cm), while the process of making the tiger took 3 hours (removing around 2000 cubic cm). On the PC, the processing required for the bowl yielded a frame rate of 25 frames per second (FPS). The tiger project required more CPU resources, allowing approximately 10 FPS. We achieved a surface accuracy of 2.5mm.

Prior to each milling task, we attached a block of foam to the table. To make the bowl, we started by removing material from the middle part of the block as well as from its corners, slowly converging to a round, thin wall shape of a bowl. When approaching the bowl's surface, we got haptic and visual feedback from changes of the spindle speed and the shaft movement. While in the beginning of the process we relied on the PC screen for orientation, later we started to recognize the model's shape, and intuitively changed to circular driving paths.

The tiger's shape was more complex and didn't expose itself easily. We chose to guide the tool along horizontal and vertical lines, removing material from one side to another. Occasionally we used deep, drill-like movements, estimating the distance from the model's surface. When recognizing the model, we slowly changed our operation, tracking the body manifold using curvature-like tool-paths. Each time there was a risk to the model from the spindle getting too close the tool prevented a crucial mistake from happening by stopping the spindle.

These milling methods were intuitively decided during the work, rather than being planned in advanced. Both artifacts were produced with a texture showing the tool-paths we chose. While the final bowl was relatively similar to its model, in the tiger project we left several areas unfinished, creating our interpretation of the design. *This demonstrates how the FreeD can be used to introduce personalization into the fabricating task of a given CAD model.*

In future work, we will further investigate issues arising from working with the FreeD. We wish to study questions such as the place of risk-taking and mistakes in the craft process, and the use of creative trial-and-error. The ability to switch the tool to a purely manual device during the work will be investigated as well as questions such as trust and reliability between the user and the computer. But above all, we would like to learn how different users fabricate the same design, giving it their subjective interpretations during the creation process.

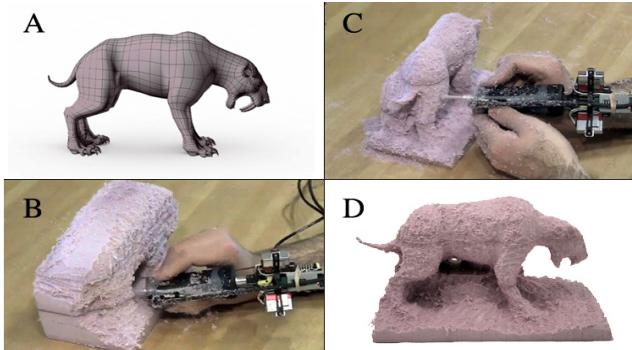


Figure 3 (A) The CAD model of a saber-tooth tiger, the fabrication process (B-C), and the final model, (D).

SUMMARY

The FreeD is a novel contribution to the growing pool of digitally-guided craft tools, allowing designers to engage

with the raw material in a new way and at the same time, integrating subtractive fabrication as part of the creative process. While digital practice separates design from fabrication, we instead suggest a synergy, allowing the creation of unique artifacts from generic designs.

The results of handcraft are unique artifacts, each subject to the judgment and care of the maker. With our work, we propose new methodology on interactive digital fabrication, considering the important qualities of traditional craft. Our overall objective is to regain intimate human control in the fabrication process, allowing CAD designers to engage expressively with a physical material.

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REFERENCES

1. Bae, S.-H., Balakrishnan, R., Singh, K. 2009. EverybodyLovesSketch: 3D Sketching for a Broader Audience. In *Proc. UIST'09*, 59-68.
2. Barillot, C., Haynor, D. R., Hellier, P. 2004. Precision Freehand Sculpting of Bone. In *Proc. MICCAI 2004*.
3. Flagg, M., Rehg, J. M. 2006. Projector-guided painting. In *Proc. UIST'06*, 235-244.
4. Gershenfeld, N. 2005. *FAB: The Coming Revolution on Your Desktop - From Personal Computers to Personal Fabrication*. Basic Books.
5. Johnson, G., Gross, M., Do, E. Y.-L., and Hong, J. 2012. Sketch it, make it: sketching precise drawings for laser cutting. In *Proc. CHI'12*.
6. Lee, J. H. 2012. Haptic Intelligentsia. StudioHomunculus website, last accessed February 10, 2012. <<http://studio-homunculus.com/>>
7. McCullough, M. 1998. *Abstracting Craft: The Practiced Digital Hand*. The MIT Press.
8. Olwal, A., Gustafsson, J. & Lindfors, C. 2008. Spatial augmented reality on industrial CNC-machines. In *Proc. SPIE 2008*.
9. Rivers, A., Moyer I. E., Durand, F. 2012. Position-Correcting Tools for 2D Digital Fabrication. In *Proc. SIGGRAPH'12*.
10. Rosner, D. K. and A. S. Taylor. 2011. Antiquarian Answers: Book Restoration as a Resource for Design. In *Proc. CHI'11*.
11. Willis, K.D.D., Lin, J., Mitani, J., Igarashi, T. 2010. Spatial sketch: bridging between movement & fabrication. In *Proc. TEI'10*, 5-12.
12. Willis, K.D.D., Xu, C., Wu, K.-J., Levin, G., Gross D. M. 2011. Interactive fabrication: new interfaces for digital fabrication. In *Proc. TEI'11*, 69-72.