The FreeD – A Handheld Digital Milling Device for Craft and Fabrication

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ABSTRACT

We present an approach to combine digital fabrication and craft that is focused on a new fabrication experience. The FreeD is a hand-held, digitally controlled, milling device. It is guided and monitored by a computer while still preserving gestural freedom. The computer intervenes only when the milling bit approaches the 3D model, which was designed beforehand, either by slowing down the spindle's speed or by drawing back the shaft. The rest of the time it allows complete freedom, allowing the user to manipulate and shape the work in any creative way. We believe The FreeD will enable a designer to move in between the straight boundaries of established CAD systems and the free expression of handcraft.

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

General terms: Design; Human Factors; Performance.

Keywords: Milling; Computer-aided Design (CAD).

INTRODUCTION

The FreeD is a hand-held, digitally controlled, milling device (Figure 1). A computer - using a magnetic motion tracker - guides and monitors the tool while preserving the freedom to sculpt and carve. The computer intervenes only when the milling bit approaches the 3D model, which was designed beforehand. In such a case, its interaction will be either slowing down the spindle's speed or drawing back the shaft; the rest of the time it allows complete freedom, allowing the user to freely manipulate and shape the work. The user can decide to keep areas of the model un-finished, or to develop a unique texture, while engaging in the fabrication process.

With The FreeD, the natural, haptic, and unconstrained engagement with the material gives the user direct feedback. For example, when the bit approaches the model, the computer will stop it from spinning, the tool will stop carving and thereby not damage the model. This feedback guides the user throughout the fabrication task, when the user is both learning and controlling the shape being fabri-

cated. With The FreeD, we hope to re-introduce the qualities of a physical engagement with a fabrication task into the realm of digital fabrication and robotics.
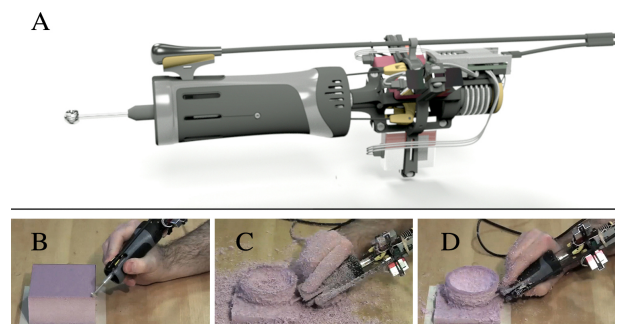

Figure 1: (A) The FreeD tool and (B-D) three photographs taken during the 30 minutes process of making a bowl, based on a CAD model, from polyethylene foam.

RELATED WORK

The Precision Freehand Sculptor (PFS) is a compact, hand-held tool that assists surgeons in accurate bone-cutting tasks [1]. The computer retracts the tool's rotary blade, using an optical tracking camera, and ensures high accuracy. While these allow accurate results, the PFS research did not explore the domain of free-form fabrication, testing the tool on a small scale, or a simple cutting task. The PFS limits the user's gestures due to line-of sight constraints of its optical tracker.

The *Haptic Intelligentsia* is a human 3D printing machine, using a robotic arm and an extruding gun. The user can freely move the gun, receiving real-time haptic feedback from the robotic arm. 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. It shares some similar motivation to ours, as can be best quoted from the maker of the *Haptic Intelligentsia*, Joong Han Lee: "the results are always unique and different, depending on how each user responds to the machine's guidance" [2].

Similar to the Haptic Intelligentsia, The FreeD allows the user to apply her/his physical modifications to a virtual CAD model, which was designed beforehand. However, it uses a subtractive method instead of an additive one, and

frees the user from the robotic arm's constraints. The FreeD enables free gestures and unconstraint movements.

SYSTEM'S ARCHITECTURE

The working environment has several parts, including an external MMTS (magnetic motion tracker system, see Figure 2). A *Polhemus FASTRAK* system (an AC 6D magnetic tracking system) was used for motion estimation, with a sensor located on the tool. The tool itself contains a milling mechanism (spindle) built on top of a long shaft connected to a DC motor. In order to control the shaft's linear movement we use a linear bearing, sitting underneath the handle. The shaft can be moved back and forth to achieve linear control on the location of the milling bit (with a dynamic range of 21mm). Three servomotors determine the shaft's linear position. An electronic element on the PCB communicates with the main computer (via Bluetooth) to control both the shaft movement and the spindle speed.
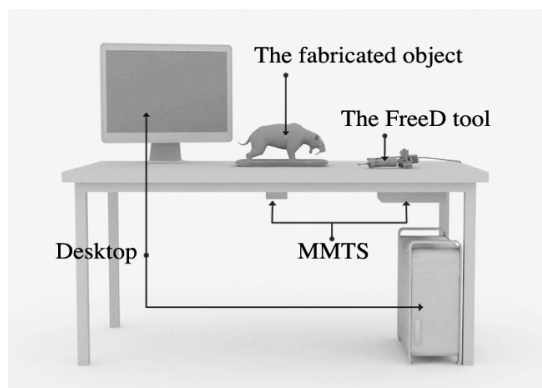

Figure 2: The FreeD's working environment.

On the computer, where the planned virtual model resides beforehand, the software is run in Grasshopper (a parametric plug-in to Rhino). The software receives as an input the tool's 6D location and orientation per request, and its outputs are commands to the control PCB on the FreeD tool. A serial communication unit maintains all data transfer with the magnetic tracker by request, and sends a command to The FreeD control PCB when ready. The mode of operation is cyclic – the software will start another round immediately after finishing the last frame. A zero order prediction estimates the next 3D position, based on the current and last positions.

The spindle's speed is a function of the distance from the model. If it is farther than 10cm the spindle won't work - at this distance the tool is in disable mode. Getting closer, the spindle operates at maximal speed, ready to mill material. If the bit approaches the model's surface (getting within 5mm range), it will slow-down to a half speed on the surface as a linear function of the distance. By that, we minimize the chance of a crucial error, forcing the user to work slowly near the surface of the object. Any prediction of the bit getting into the model will issue a command to shutdown the spindle.

The shaft control is a bit more complicated, taking into consideration the angle between the shaft and the normal to the model's surface. The software will try to minimize the chances the bit will enter the volume of the model, drawing it back as much as possible. When the bit moves farther from the surface, the software will push the shaft back to its original position.

DISCUSSION

The tool was tested by milling two models in polyethylene foam –a bowl and a prehistoric tiger. In the bowl project, it took us 30 minutes to remove an estimated 120 cubic cm of material. In the tiger project, it took us 3 hours to cut an estimated 2000 cubic cm of material. On the PC, the processing time for these projects varied 10 to 25 FPS, and the milling accuracy of the work was 2.5mm.

We started each carving task by first aligning the foam to the axis origin of the virtual environment, where the CAD model was positioned. To produce the bowl, we started by removing material from the middle part of the block, as well as from its corners, converging slowly to a round, thin wall shape of a bowl. When approaching the bowl's surface, we got haptic and visual feedbacks from both the spindle speed and the shaft movement. When we removed enough material to approach the bowl's surface, we were able to "discover" the shape in the foam. The "trial and error" nature of the work changed slowly to a more constructive, circular driving paths. When our free movements were not accurate, putting the model into risk, the tool prevented a crucial error from happening by stopping the spindle's rotation.

Since the tiger's shape is more complicated and cannot be discovered by just few deep millings, we took a slightly different approach. We guided the tool along horizontal and vertical lines, removing material slowly from one side to another. Once in a while we used a more deep, drill-like movement, estimating the distance from the model's surface. When the model started appearing, we changed our operation, slowly tracking the body manifold using curvature-like tool-paths.

Both the bowl's and the tiger's finished objects have a bit of a milling texture on their surface. This is a unique signature of the manual milling process – had we chosen a different tool-path, we would have ended with a different texture. By engaging with the material and the model during this fabrication task, we demonstrate how The FreeD can be used to achieve authentic and unique results.

REFERENCES

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