The Hybrid Artisans: A Case Study in Smart Tools

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We present an approach to combining digital fabrication and craft, demonstrating a hybrid interaction paradigm where human and machine work in synergy. The FreeD is a hand-held digital milling device, monitored by a computer while preserving the makers freedom to manipulate the work in many creative ways. Relying on a pre-designed 3D model, the computer gets into action only when the milling bit risks the objects integrity, preventing damage by slowing down the spindle speed, while the rest of the time it allows complete gestural freedom. We present the technology and explore several interaction methodologies for carving. In addition, we present a user study that reveals how synergetic cooperation between human and machine preserves the expressiveness of manual practice. This quality of the hybrid territory evolves into design personalization. We conclude on the creative potential of open-ended procedures within this hybrid interactive territory of manual smart tools and devices.

Categories and Subject Descriptors: H.5.2 [**Information Interfaces and Presentation**]: User Interfaces

General Terms: Computer-Aided Design (CAD); Craft; Digital Fabrication; Carving; Milling; Personalization

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1. INTRODUCTION

Cyril M. Kornbluth, in his short sci-fi story "The Little Black Bag," describes a highly automated medical tool kit. The tools in the kit were smart, assisting the surgeon by preventing him from hurting healthy tissue during the operation [Kornbluth 1950]. Later, in one 1988 episode of *Star-Trek: The Next Generation*, we are first introduced to an unusually shaped wood-sculpting tool that allows unskilled makers to sculpt in wood [Roddenberry et al. 1988]. Drawing lines from these preliminary concepts, in the past several years researchers have started to develop smart tools that work in conjunction with human operators. Our hope is to substantiate the importance of engaging in a discourse that posits a new hybrid territory of artifacts produced by both people and computers, incorporating subjective decision-making in the fabrication process (Figure 1), and blurring the line between design and fabrication.

Digital fabrication technologies have altered many disciplines over the past several years [Gershenfeld 2008]. 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

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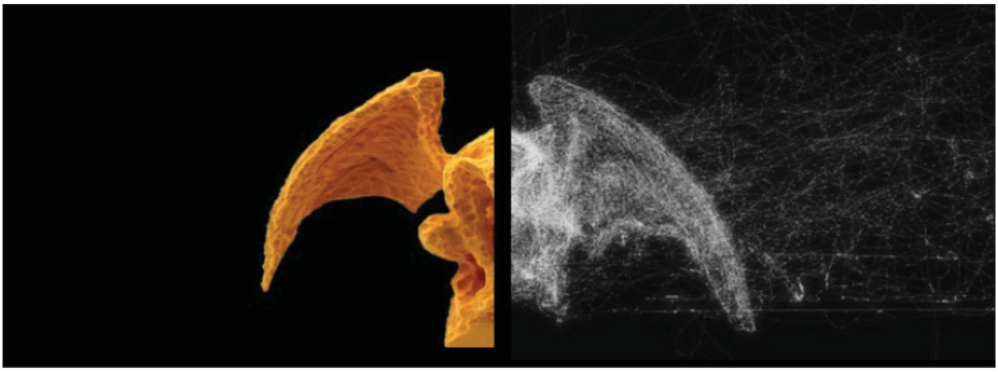


Fig. 1. Visualization of hybrid practice: one side of a gargoyle sculpture (280mm width) made with the FreeD (left) and the tool-path projection of the other side (right).

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 this technology matures. However, qualities such as creative engagement in the experience of making are lost, while the nature of interaction with the fabricated artifact is rarely the focus of new developments.

Although the process of engineering minimizes risks, seeks efficiency, and enables automation and repetition, craft is about involvement and engagement, uniqueness of the final products, and authenticity of the experience [McCullough 1998]. 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 meanings [Rosner and Taylor 2011].

Our research interest lies in the cross-section between digital fabrication and the study of the craft experience. With this work, we hope 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.

FreeD is a freehand, digitally controlled milling device (Figure 2(b) and (c)). With FreeD, we harness CAD abilities in three-dimensional (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 case, it will slow down the spindle; the rest of the time, it allows the user to freely shape the work. In addition, FreeD allows manual and computational design modification during fabrication, rendering a unique 3D model directly in a physical material.

In the course of this work, we discuss different hybrid interaction methodologies. Although the tool assists inexperienced makers in carving complex 3D objects (static-model mode), it also enables personalizing and changing of the underlying model (dynamic-model mode). In the second case, FreeD doubles as an input device, where the user moves and the computer reacts. We present several novel modes of interaction, such as switching between virtual models through the work, overriding the computer, deforming a virtual model while making it, or searching interactively for an optimal parametric model. In addition, the new tool can operate independently for tasks such as semi-automatic texture rendering.

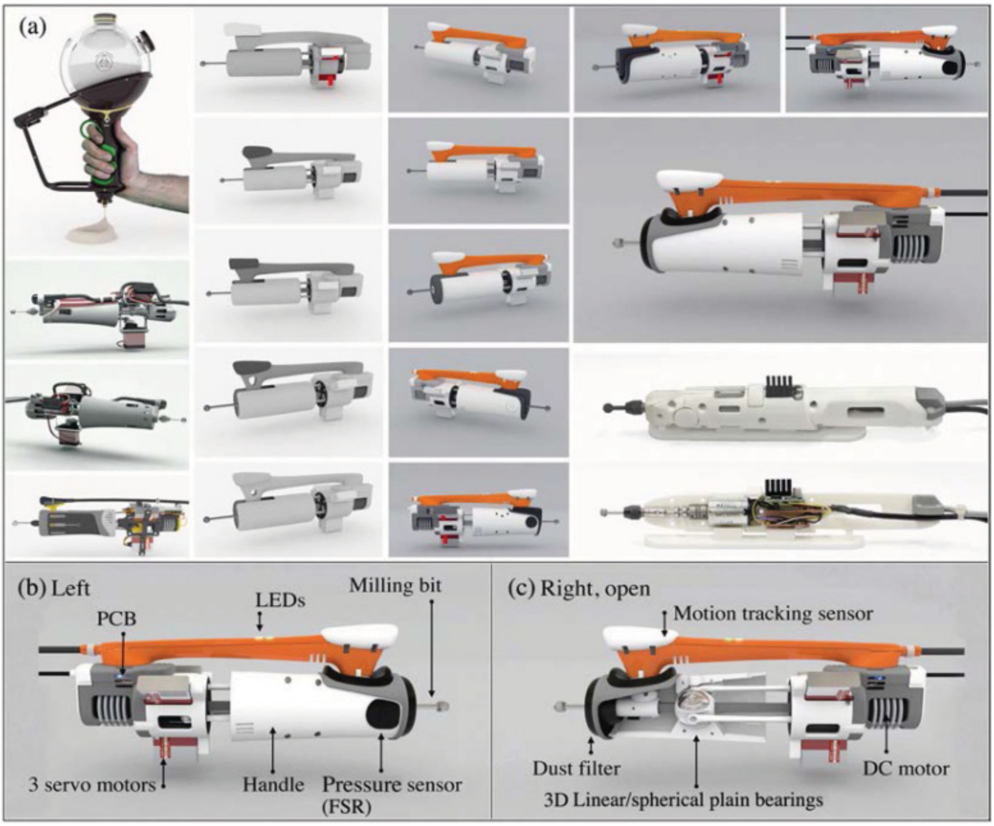


Fig. 2. (a) Top left to bottom right: a rendering of an early design concept of an additive device; a rendering of early subtractive prototypes; renderings of iterations of the FreeD presented in this paper and photos of the latest working version. Renderings of the FreeD design discussed in this chapter: (b) left side view of the tool, with its main components, and (c) a right side view of the opened device.

In addition to the technical details of the FreeD, which were already presented elsewhere [Zoran et al. 2013; Zoran and Paradiso 2013], we present an extended user study combining quantitative and qualitative evaluation with experienced makers. The study supports our initial hypothesis that hybrid interaction contributes to a personalization of the fabricated object and that the nature of tactile, hands-on engagement has an impact on design decisions during the process that supports the maker's style and identity, even in the case of fabricating a static model. In addition, the study sheds light on the subjective perspectives makers take on the hybrid practice, which will help in defining crucial roadmaps to clearly develop this hybrid interaction territory.

2. 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 two-dimensional (2D) creative domain of painting and sketching [Bae et al. 2009; Flagg and Rehg 2006; Johnson et al. 2012], and others enable 3D creative outputs, from 3D CAD output [Willis et al. 2010], to the control of the fabrication of 3D objects. Willis et al. developed several devices using real-time inputs to construct physical forms [Willis et al. 2011]. Olwal et al. [2008] combined a computer graphics interface with physical objects, working with a lathe. Rivers et al. [2012b] developed a position-correcting 2D router, achieving accurate cuts on large-scale surfaces while allowing free guidance of the tool.

In the computer graphics (CG) domain, an ample amount of research was put into nonphotorealistic (NPR) rendering of images to mimic man-made painting or sketches. However, a recent comprehensive survey on NPR shows that the measure of success of many algorithms is a numeric function of “beauty” to be optimized [Kyprianidis et al. 2013] and not the expression or subjectivity of the creation. Recent work tries to computationally model the artistic style of a small number of artists through learning their strokes without the goal of beautifying the output [Berger et al. 2013]; however, this is an exception to a large movement in CG research that looks for precision, beautification, and averaging, a recent example of which is Zitnick [2013].

A similar 3D interaction concept is the Precision Freehand Sculptor (PFS), a compact, hand-held tool that assists surgeons in accurate bone-cutting tasks [Brisson et al. 2004]. The computer retracts the tool’s rotary blade based on data from an optical tracking camera to ensure high accuracy. A few other approaches for the integration of robotic systems in surgical operation were studied in the past. The da Vinci Surgical System enables surgeons to perform delicate operations remote from the patient, with increased visibility, precision, dexterity, and control [Surgical 2013]. In their early work, Dario et al. [2003] analyzed and reviewed robotic systems for computer-assisted surgery and presented a classification of such systems based on the degree of “intelligence” of the devices. A new approach was presented by Zahraee et al. [2010], who studied the kinematics of the end effector in a robotic hand-held surgical device for laparoscopic interventions to improve the surgeon’s dexterity. Stetten et al. [2011] presented a method for magnifying forces perceived by an operator using a tool to create a proportionally greater force between the handle and a brace attached to the operator’s hand.

These last projects allow accurate results, but they do not explore the domain of a free-form 3D fabrication, instead focusing on aligning the device’s cutting head to a predesigned tool path. A more relevant example is the Haptic Intelligentsia, 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 [Lee 2012]. 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 the criteria for a freeform hand-held device, a major interactive quality in our work.

Additional concepts assuming purely manual practice were previously implemented by 3D clay sculpting with bare hands or manual tools [Skeels and Rehg 2007; Rivers et al. 2012a]. We found Copy-CAD by Follmer et al. [2010] especially interesting, allowing users to copy 2D elements of physical objects, reassemble, and then fabricate these elements into a new 2D shape.

FreeD can be used to modify the virtual model during the work. Gustafson et al. [2010] studied the use of hand gestures in free air as a control input for a virtual shape without visual feedback, Song et al. [2006] used annotation squiggles with a pen, Arisandi et al. [2012] employed specialized hand-held tools, and Cho et al. [2012] used a depth camera to track hand gestures in shaping a virtual object using a virtual pottery wheel. Recently, similar ideas were integrated with fabrication technologies, such as laser cutters [Johnson et al. 2012; Mueller et al. 2012] or the RepRap 3D printer [Patel 2011].

3. DESIGN AND TECHNOLOGY

The FreeD device is one element in a complete systemthat contains the hand-held tool, a magnetic motion tracking system (MMTS), the fabricated object, a computer, and

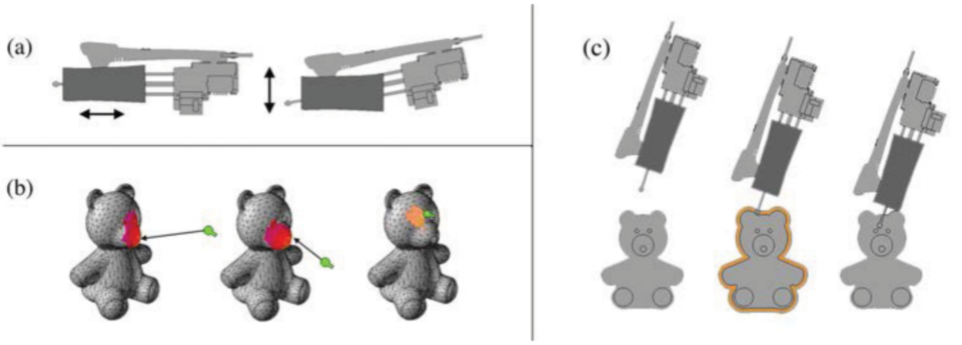


Fig. 3. (a) The multiple-axis bearing allows the milling bit to move in 3 degrees of freedom: 2 in the carving plane, and a forward-backward motion. (b) Heat-map visualization of the risk zone. (c) Risk management with the FreeD: low, high, and penetration level of risk.

software distributed over the computer and the tool. The tool is usually held with one hand, while the user is free to move it in 3D, limited only by the length of power cables and the MMTS. Over a period of a year and a half, we developed several versions for the tool (Figure 2(a)); the one presented here was previously discussed in Zoran et al. [2013] under the name FreeD V.2.

The FreeD, with an overall weight of 300g, contains a custom milling mechanism (spindle) built on top of a long shaft (Figure 2(b) and (c)) with a 12V DC motor (MicroDrives M2232U12VCS with up to 10,000 RPM with no load, and up to 5.2mNm torque). A custom 3D bearing mechanism is located underneath the handle, sitting above the titanium shaft, and enabling three degrees of freedom (DOF) movements at an approximate spherical volume of 20mm (see Figure 3(a)). Three servomotors (MKS 6125 mini servos, with up to 5.8kg-cm for 6V), aligned perpendicular to the shaft near the spindle motor, determine the shaft's position. An electronic circuit on the PCB (with an ATmega328 microprocessor and a MC33926 motor driver, powered with 5V and 12V signals) communicates with the main computer via Bluetooth to control the shaft movement and the spindle speed.

A Force-Sensing Resistor (FSR) sensor is located on the handle, allowing the user to override the computer. The DC motor speed (S_p, where 1 is the maximal value) is a linear factor of the pressure read from the FSR (P_r, when 1 is maximal value) and the risk to the model (R_s, 1 is maximal risk see Figure 3(c)):

$$S_p = 1 - R_s(1 - P_r). \tag{1}$$

Two LEDs are located on the tool, providing the user with visual feedback. The first LED's blinking frequency correlates to the pressure detected by the FSR. The frequency of the second LED corresponds to the distance between the bit and the surface of the model (when the bit touches the model's surface, the light is constant). In addition, the operating frequency of the DC motor (PWM), controlled by the motordriver, changes from ultrasonic to an audible range (around 2KHz) to give the user an alarm when the bit is within 4mm of the model surface.

The major part of the computation is done on a general-purpose computer (Alienware M14x Laptop with i7-3740QM Intel core, 12GB DDR3, and 2GB NVIDIA GeForce GT 650M graphic card). The computer also provides the user with a visual feedback on the screen (see Figure 3(b)). For tracking (MMTS), we use 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).

On the computer, where the virtual model resides, the software runs in Grasshopper and Rhino. The input is the 6D location and orientation of the tool, and the outputs are commands to the control PCB on the FreeD. A prediction of the next position of the bit is extrapolated by a spline of the 4th order (using the current location and the three previous ones). The software calculates the distances (D) to the CAD model (using Rhinoscript function MeshCP()) from both the current location and the predicted one, estimating which point puts the model at higher risk (i.e., closest to the model). Although the DC motor's speed is calculated on the tool as a factor of P_r and R_s, the parameters themselves are calculated by the main control software (values in mm):

$$R_s = \begin{cases} 0 & \text{if } D \leq 100 \text{ and } D > 4 \\ D/8 & \text{if } D < 4 \text{ and } D > 0 \\ 1 & \text{elsewhere.} \end{cases} \tag{2}$$

The default shaft position is fully extended, with a 20mm potential to absorb the offset and retract. Unlike an early work [Zoran and Paradiso 2012, 2013], in the current FreeD design, we use the servos for an independent tool operation rather than a penetration protection mechanism.

4. OPERATION AND INTERACTION

To operate the FreeD, the user typically sits in front of the material (balsa foam), which is attached to a wooden table. The physical working area is calibrated to the virtual workspace. He is free to investigate any milling approach, such as extruding lines, drilling holes, trimming surfaces, or using an arbitrary pattern. The computer slows down the spindle as the bit approaches the model, stopping it completely before it penetrates the virtual model. This enables the user to cut along the boundary of the virtual model where desired. He can leave parts of the model unfinished or override the computer by using the pressure sensor. Later, we will discuss modes of operation in which the system can dynamically alter the model based on user actions or operate autonomously.

While milling, the FreeD responds to the user's actions when these 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 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 he 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.

In addition, trying to ameliorate the maker's inability to visualize the model embedded in the material, we experimented briefly with an Augmented Reality head-worn device that shows the virual model superimposed on the raw material. We aligned the 6 DOF input from the MMTS with a markers-based tracker and used a depth-buffer stencil drawing transparency to mask out a model of the FreeD so it would appear above the augmentation (Figure 4). This solution attempts to evoke the feeling of looking inside the material and seeing the model while carving. However, more work is yet required before we can integrate this technology seamlessly with the FreeD, and it is a subject for future work.

In this subsection, we survey several original interaction modes with the FreeD as presented in Zoran et al. [2013]: the static CAD model mode in which the computer assists only by preventing the user from damaging the model; a dynamic mode, in which the computer numerically controls the model, responding to the user's actions; and the autonomous mode, in which the computer can operate independently of the

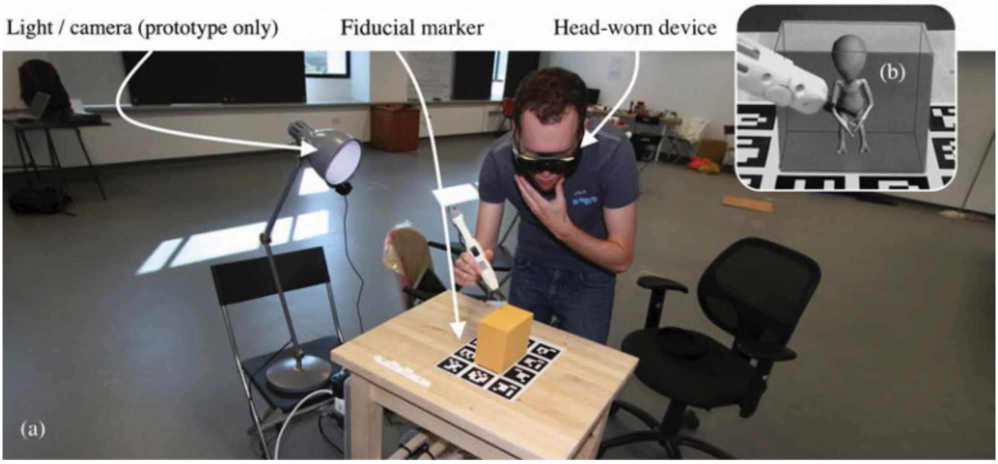


Fig. 4. (a) A head-worn Augmented Reality assistive system for the FreeD. (b) The FreeD tool occludes the augmentation graphics.

user for tasks such as semiautomatic texture rendering. Together, these modes span a new space, one in which both human and computer work in synergy to contribute to the final product.

4.1. Fabrication of Static Models

In the fabrication of a static model, the user cannot alter the CAD model, and the boundary of the virtual object remains static. This approach resembles traditional digital fabrication technologies, where the virtual model is fixed and prepared beforehand. Here, however, the user (rather than an automatic process) determines the tool-path. This enables personalization of the work and may also circumvent complicated CAD challenges such as merging 3D elements into a single object.

4.1.1. Tool-path Personalization. As discussed earlier, the FreeD gives the user direct control over the milling tool path. The final surface smoothness and resolution are determined by the size and shape of the bit and the tool path. Usually, in fabrication, a manual process renders a chaotic surface pattern, whereas an automatic process renders an organized network of marks. This is mainly because in a manual tool path, as a consequence of the maker's dexterity and patience, the operation never repeats itself and evolves into a unique texture, for example, in the fabrication of a sabertooth tiger model (Figure 5(a)). The final texture reflects the user tool path, properties of the material, bit size, and latency of the system. The parts left unfinished (legs) demonstrate decisions made during the work. Tool paths can be saved, allowing an analysis to extract an artistic style.

4.1.2. Physical Merging. Because the FreeD encourages the user to work intuitively, the user can switch between different reference virtual models during the work. The fusion of these models need not be determined numerically, only physically, relinquishing the need to solve mesh intersection problems in making a single CAD model, as in the merging of a sabertooth tiger model with dragon wings and deer horns (Figure 5(c)).

4.1.3. Manual Override. Here, we present an approach foreign to most digital fabrication methods: allowing intentional destruction of the fabricated model. By overwriting the computer, the user minimizes digital control on the shaft while keeping the advantage of digital guidance with a sonic alarm and LED. In addition to leaving parts unfinished,

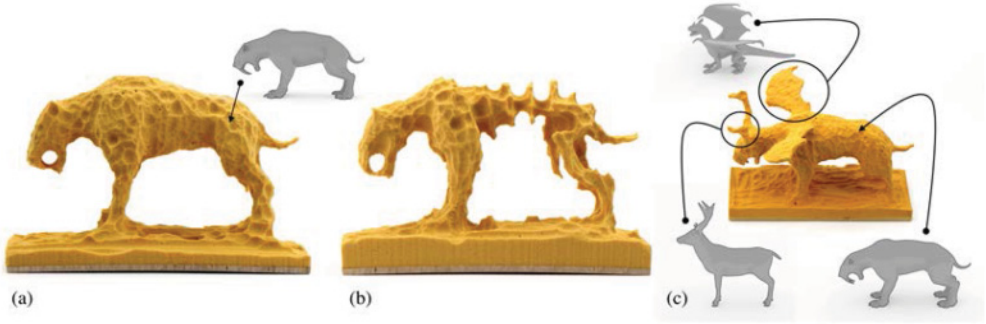


Fig. 5. (a) Sculpting a static model of a sabertooth tiger (80min fabrication time, length 125mm) based on a 3D model. (b) The result of overriding computer guidance is a completely different design (90min fabrication time, model length 120mm). The artist takes risks and produces a unique artifact. (c) Hybridization of meshes while sculpting (100min fabrication time, model length 120mm). The final 3D shape does not exist virtually; it only exists in the carved model.

the maker can intentionally "damage" the model, working around or inside the virtual shape, thus allowing for improvisation. Beyond Figure 5(a), in Figure 5(b) the user continued to manually remove parts of the model to achieve a unique artifact.

4.2. Fabrication of Dynamic Models

Today, digital fabrication technologies require models to be designed beforehand, and no changes can be made during fabrication, as in the static approach presented in the last section. In contrast, craftpersons are free to deform the subject during the making process, as long as there is enough material left. Aiming to recreate this freedom, we present a novel capability to allow the modification of dynamic virtual models during fabrication, exploring three types of interaction with dynamic models: direct shape deformation, volume occupancy optimization, and data-driven shape exploration.

4.2.1. Direct Shape Deformation. The first-order dynamics in our interaction model is to allow for direct deformation of a CAD model. Unlike manual overriding of a static model, in direct shape deformation, the computer keeps track of subtracted material: when the user presses the override button and penetrates the virtual model, the computer deforms the mesh to ameliorate the penetration.

Recent related methods of mesh deformation [Sorkine et al. 2004] seek to preserve local features under deformation. Here, we used a simplified weighting scheme for local deformation with respect to the user's action. As the weights for the offset vector of vertices (O_v, where v is the vertex index), we use a Gaussian decay over the distance from the nearest vertex to the bit, to create an effect of a smooth deformation:

$$O_v = T_v * \exp\left(0.005(10 - P_r)^2\right). \tag{3}$$

Where P_r is the value read from the override FSR button (0 is no pressure and 1 is maximal pressure), T is the penetration vector (the vector between the point of first contact to the deepest bit position), d_v is the distance from v to the penetration point, and S is the number of affected vertices, a constant number that can be defined by the user (and thus define the affected area). See Figure 6 for an example of deforming a mesh while fabricating.

4.2.2. Volume Occupancy Optimization. Further examining the art of carving, we face a common challenge: fitting a shape to a given volume of material, for example, in the case of an irregular piece of wood, where the artist may try to maximize the volume

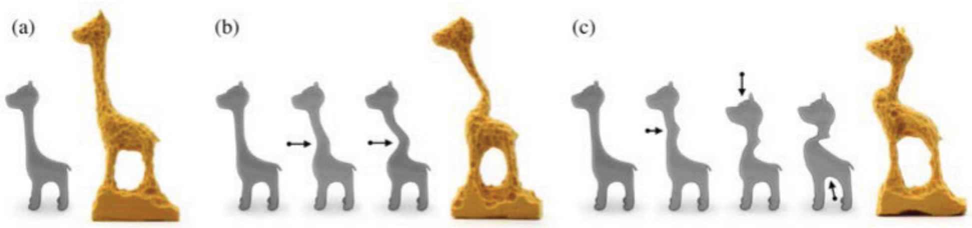


Fig. 6. Model deformation while carving using the override mechanism. The model is smoothly deformed in proportion to the bit's penetration of the material. (a) The original model, (b) deformation from the left, (c) and deformations of the model from multiple directions.

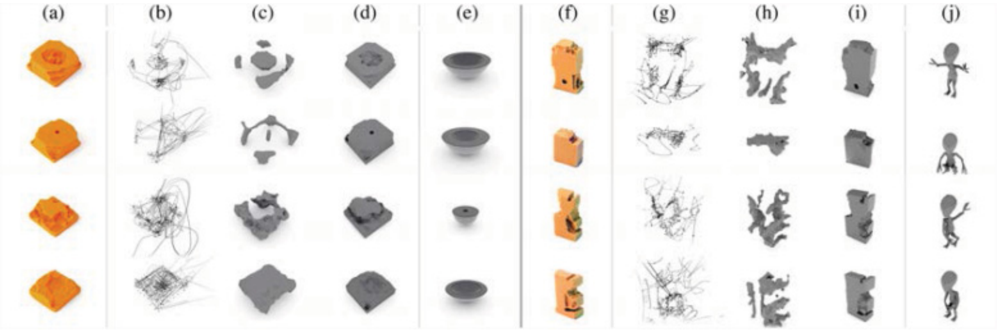


Fig. 7. An initial iteration in a parametric fitting process of bowl and humanoid forms: (a) and (f) the physical carved material; (b) and (g) renderings of the tool path; (c) and (h) simulations of the material removed by the tool; (d) and (i) simulations of the remaining material; (e) and (j) result of the fitting algorithm.

of the shape while bounded by the material. The FreeD allows working in this fashion using optimization of volume occupancy. We illustrate the idea of volume occupancy optimization through a simple parametric bowl with three parameters: inner and outer radii (r_i, r_o) and height (c). Let us denote $\Theta = \{r_o; r_in; c\}$. Spheres and cubes were used to create the model of the bowl with Constructive Solid Geometry (CSG) boolean operations (using the Carve CSG library [Sargeant 2012]). See Figure 7(e) for examples of parametric bowls.

In order to fit a shape in the material, we first determine the remaining volume. After the FreeD carves out a part of the material, we keep only the tool-path points that are inside the volume in question (see Figure 7(b)). Each point describes only the center of the bit, we therefore randomly generated 10 points on a sphere with radius 3.2mm (the real bit size) to simulate the whole bit as it passed through space. A solid shape is created out of the point cloud using the Alpha Shapes method [Edelsbrunner and Mücke 1994] (see Figure 7(c)). Once the removed portion is established, the remaining volume is easily obtained with a boolean CSG operation (see Figure 7(d)).

A parametric bowl is then fitted inside the remaining volume by a score function vector, whose norm should be minimized:

$$\begin{aligned} f_1(\Theta) &= \omega_1 * V_{remain}(\Theta) \\ f_2(\Theta) &= \omega_2 * V_{out}(\Theta) \\ f_3(\Theta) &= \omega_3 * (1 - c) \\ f_4(\Theta) &= \omega_4 * (1 - r_in) \\ F(\Theta) &= [f_1(\Theta); f_2(\Theta); f_3(\Theta); f_4(\Theta)]. \end{aligned} \tag{4}$$

The $V_{remain}(\Theta)$ marks the remaining volume of material after the bowl was subtracted and $V_{out}(\Theta)$ marks the volume that the bowl takes outside the remaining volume (i.e., out in the air). These measures should be minimized so as to maximize occupancy and minimize escape. The bowl is made as high and thick as possible using the final two residuals. We used a nonlinear least-squares solver [Agarwal and Mierle 2012] to find the solution for the canonical optimization problem: $\arg\min_{\Theta} ||F(\Theta)||^2$. Due to the CSG operations, the function is evaluated numerically.

4.2.3. Data-Driven Shape Exploration. In this dynamic model mode, we strive to simulate the unbounded amount of possible outcomes that manual carving allows. Using a vast database, the tool guides users while exploring the shape-space in an interactive process. We work with a hierarchical database of more than 4,000 examples of human poses that were recorded with the Kinect sensor via the OpenNI software stack [OpenNI 2012]. The poses were clustered using a K-Means variant into 50 clusters (meta-poses) of varying sizes, using WEKA [Hall et al. 2009]. Then, we use the method from Baran and Popović [2007] to auto-rig the humanoid alien model to a skeleton model that corresponds with the Kinect. For deformation of the mesh, we used the canonical Linear Blend Skinning method.

The process of finding the remaining volume (see the previous subsection) is repeated. Then, an exhaustive search over the database is performed to find the meta-pose that has the least amount of escape from the remaining volume (V_{out}), followed by a search within the best-found cluster. Every iteration presents several options for advancement that the user can choose from. After the database search, fine-tuning ensues for the position of the limbs and for small translations of the entire shape in respect to the volume (see Figure 7(f–j)).

4.3. Autonomous Operation Mode

Digital fabrication technologies incorporate several degrees of automatic motion, while common hand-held fabrication devices do not automatically move but are manually controlled. The use of automatic motion in hand-held devices is rarely considered. Lately, this preconception is changing, as demonstrated by Rivers et al. [2012b], integrating a 2D actuation mechanism to correct users' paths, and in the early FreeD version [Zoran and Paradiso 2013], where shaft retraction prevents the user from accidental penetration of the model.

An independent actuation of the shaft operates semiautonomously: while the user holds FreeD and makes large-scale movements, the tool makes autonomous smaller scale movements. For example, the tool is operated as a semiautonomous milling device. In Figure 8, we demonstrate a semiautonomous texture rendering: when the bit is closer than 4mm to the fur segment, the servos operate with a linear pecking movement (4Hz, 5mm movement range) to achieve a fur texture. The user continues to operate the tool freely, unconstrained by the shaft actuation.

5. PERFORMANCE AND EXPLORATION

In this section, we first present statistical performance measurements collected while working with the FreeD before discussing the experience of using the tool and the user study in the next section.

5.1. System Performance

The FreeD system was used in the fabrication of 17 complete artifacts, in addition to several 3D sketches and a few preliminary sculptures. We tested the tool by carving in both high- and low-density balsa foams, basswood, and carving wax. All of the studies presented here were done in foam, since it took up to 10 times longer to machine wax

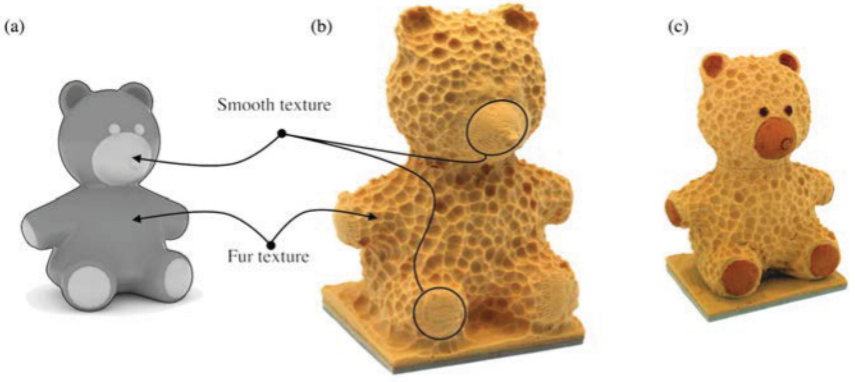


Fig. 8. Teddy bear model (height 147mm) (a) embellished with fur textures. The mesh is encoded with a rough or smooth texture. (b) The rough texture causes the shaft to move back and forth, creating dimples in the material that simulate fur. (c) Finally, we finished the work manually by sanding and then painting the smooth areas.

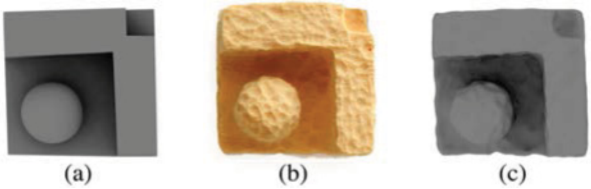


Fig. 9. An examination of the FreeD V2s accuracy measure. (a) the virtual model (53mm length), (b) the model fabricated with FreeD, (c) a 3D scanning of the fabrication. The RMS error is less than 0.5mm.

and wood. The control software updated at a frame rate varying between 8 and 20 frames per second (FPS). We worked with mesh models of 150 vertices (humanoid) to 5,370 vertices (gargoyle), lengths between 120mm (giraffe) to 280mm (gargoyle), and with production times of 40 minutes (giraffe) to 5 hours (gargoyle). The static-bit accuracy (measured by holding the bit in one place while rotating the tool around it) varies between 0.05mm RMS (20cm from the magnetic field generator) and 0.4mm RMS (70cm away).

While in our work we seek personalization of artifacts rather than production accuracy, we nevertheless found it important to test how accurately the FreeD can reconstruct a predesigned virtual model. The surface accuracy depends on the frame rate, tool movement speed, and material density. For example, with 15 FPS and 350mm/sec attack speed, the bit penetrated 3.5mm into a dense balsa foam before the system shut down the spindle rotation.

To empirically evaluate the accuracy of FreeD, we designed a model with right angles and a sphere, fabricated it with the FreeD, and then scanned it with Konica Minolta VIVID 910 scanner to computationally estimate the error (see Figure 9(a–c)). We present the following results only to give a general sense of accuracy, as the adherence of the resulting surface to the virtual model is greatly a factor of the maker's dexterity and patience, a complex concept to quantify. The resulting error was smaller than 0.5mm RMS (samples for this measurement were taken within a grid of less than 1mm resolution). As expected, because of the bit size, FreeD fails to clear out material from sharp corners; however, all subtractive fabrication methods suffer from this drawback.

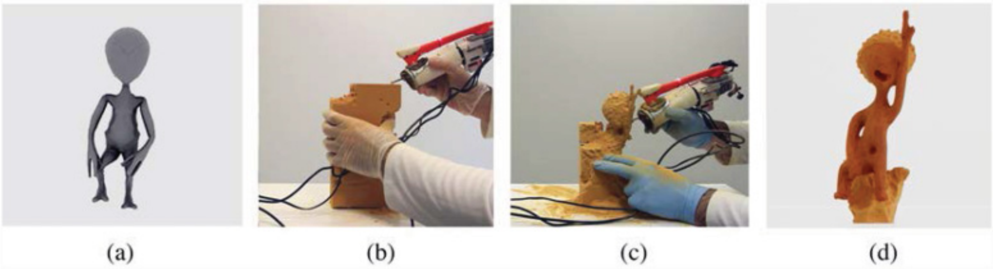


Fig. 10. Fabrication of a humanoid model (height 222mm) illustrating all methods. (a) The initial model. (b–c) Evolution of the model as material is removed. Texturing hair and deliberate penetration of the model to carve a mouth and navel. (d) The final artifact, after manual finish (sandpaper smoothing and painting).

5.2. Full Capabilities Integration

We demonstrate the making of a larger-scale model that incorporates most of the functionalities of the tool (see Figure 10(a–d)). We made an alien figure, which features a large head and elongated arms. The work began by interactively exploring the skeleton database in the same manner we discussed earlier.

When a satisfying pose was found, we began removing larger chunks of material. Using the shape deformation method described earlier, we created a dent in the model to emphasize the sideways motion of the hips. We then kept removing material until the general form was fleshed out and moved on to texturing and decorating. On the computer, we set the alien's head to have a rough texture that will resemble hair. Finally, we used the override mechanism to create completely unguided carvings of the mouth and navel and decided to leave part of the model unfinished.

5.3. Collaborative Experience

Any manual process that requires a high level of expertise introduces a challenge for collaborative work. The makers' dexterity and their subjective intention cannot easily be communicated with collaborators, unless they are trained in working with each other. FreeD can simplify this challenge. The inherent digital registration of a single CAD model guarantees that all makers rely on the same reference. For example, five participants (in addition to the authors) successfully collaborated on a single carving task of a large deer sculpture without the need to communicate or transfer any information prior to the work (Figure 11).

6. USER STUDY

Our objective with the FreeD is to demonstrate the importance of the hybrid fabrication territory, where artifacts are produced by both people and computers. We advocate for values rarely considered within the contemporary fabrication movement, such as intimacy and the uniqueness of the experience.

The evaluation of the FreeD presents a challenge. Although a quantitative study of the performance of the FreeD is useful, it may not provide information on the subjective qualities of the experience of using the tool. Due to the hybrid nature of the work, the study presented here incorporates both quantitative and qualitative methods. For the quantitative portion of the study, we recorded users' tool paths and processed them to detect patterns in workflow and technique. For the qualitative portion, we had discussions with the participants about their experiences and perceptions of the process. In this process, we seek correlation between the makers' practices, their workflow, technique, experience with the FreeD, and the produced artifacts.

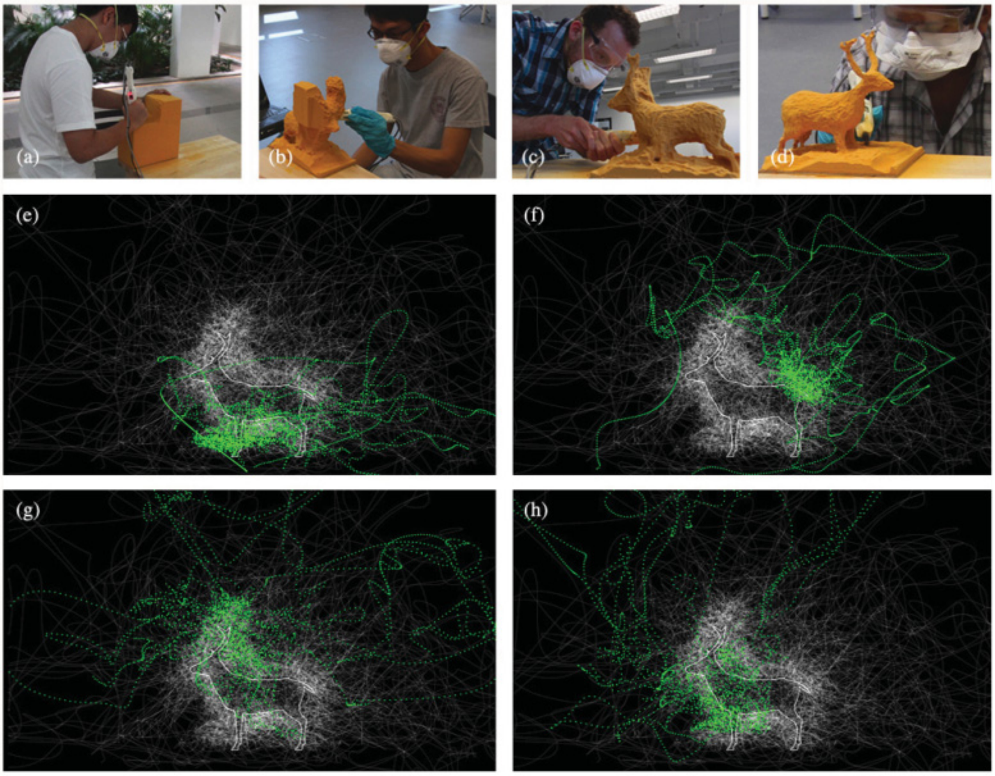


Fig. 11. (a–d) Collaborative effort in creating a deer artifact. (e–h) Four tool-path visualizations illustrate each individual participant's work (green) vs. the whole group (white).

In addition to investigation of the FreeD experience, this study explores future potential of hybrid interaction with smart tools in general. All participants were selected because they had a personal interest in the combination of manual and digital fabrication practices. Five participants took part in this study; all of them had prior design and fabrication experience, varying from traditional violin-making to digital fabrication and robotics, and each person had some level of CAD skills. Most participants spend their professional life in front a computer. We selected people with computational experience over handcraft experts in order to primarily evaluate the FreeD as a supportive tool for computer users and less so as a technology for traditional craft masters.

6.1. Related Studies

Several prior projects inspired this study. Harold Edgerton and Gjon Mili [2010] (see Figure 2.19) used multiflash photographs to capture a golf player's swing motion, dancers' movements, and tennis players, to recent gait detection with a variety of sensors [Lee et al. 2006]. Lapinski et al. [2011] developed a multisensor acceleration system to study the pitch motion of professional baseball players. These studies focused on observing transient professional actions, whereas we are seeking a multidimensional, high-entropy behavior that takes place over a long period of time. A similar motivation is present in a work by Berman et al. [2013], where they studied the behavioral space of flies using statistical methods. This work in particular inspired the quantitative section of our study.

On the qualitative side, we build on few important projects ato structure the method of our interviews. Adding to the discussion in the beginning of this chapter, Mishler [1999] conducted inspiring interviews with professional craftpersons “who reflect on their lives and their efforts to sustain their form of work as committed artists in a world of mass production and standardization,” drawing narratives of identity and their relationships to processional practices. Turkle and Papert [1991] argued that “computers are a medium through which different styles of scientific thought can be observed,” a fundamental observation within our work, justifying the hybrid territory of making. On a closing note, studies of skill and style to reveal symbolic communication are common ethnographic and archeological practices [Hurt and Rakita 2001; Wiessner 1983] and influence our attention to aesthetical and stylistic details.

6.2. Hypothesis and Objectives

Our initial hypothesis was that through tactile engagement during the creative process, makers introduce personal style with a potential to impact an initial design concept. The FreeD system allows, for the first time, makers with no carving background to participate in a study in which they are evaluated side by side with professionals. In addition, we assumed that participants’ personal creative narratives affect their design style. Therefore, preserved elements of personal design style should be evident in their use of the FreeD. Finally, we used this study to explore concepts of synergy between human intimate involvement and digital control by engaging people in a form of hybrid interaction that may go beyond the practice of fabrication, craft, or design, reconsidering human interaction with digital systems.

6.3. Method

Five participants took part in the study; each of them fabricated the same 3D cat model out of balsa foam, using the FreeD (see Figure 12). Before they began the fabrication process, we interviewed each participant for 45 minutes. The interviews consisted of a discussion of the participants’ practice, their expectation from the experience of working with the FreeD, and their objectives in merging of digital and manual forms of fabrication.

For the study, we pre-cut all the balsa stock to an initial contour and initialized and calibrated the system before the participants began their own work. The participants could choose to rely on visual feedback from the laptop, placed 1 meter away from the workbench, showing the location of the milling bit with respect to side and front views of the model. The tool paths (6 DOF and value of the pressure sensor) were recorded as they were sampled by the control system.

Immediately after the participants finished the work, we interviewed them about their reflections on the experience. A few weeks later, we followed up with a closing interview, investigating questions regarding ownership of the work and conceptual perspective on the integration of digital technology in the fabrication practice. In the next section, we introduce the participants, their practice, and their work with the FreeD. Following that, we present the statistical evaluation and a closing discussion.

Because we are seeking a technology that can express subjectivity, rather than hiding it, we choose to present participants’ practice, objectives, and experiences and to use their name unmasked in the article (by permission). Moreover, we believe that the users’ biased personalities are clearly impactful to the fabrication process: they have unique stories, and they cannot be fully objective.

6.4. Five Makers, Five Projects

During the study, one of our initial observations was that all users share similar procedures when working with the device. The tool was first guided away from the

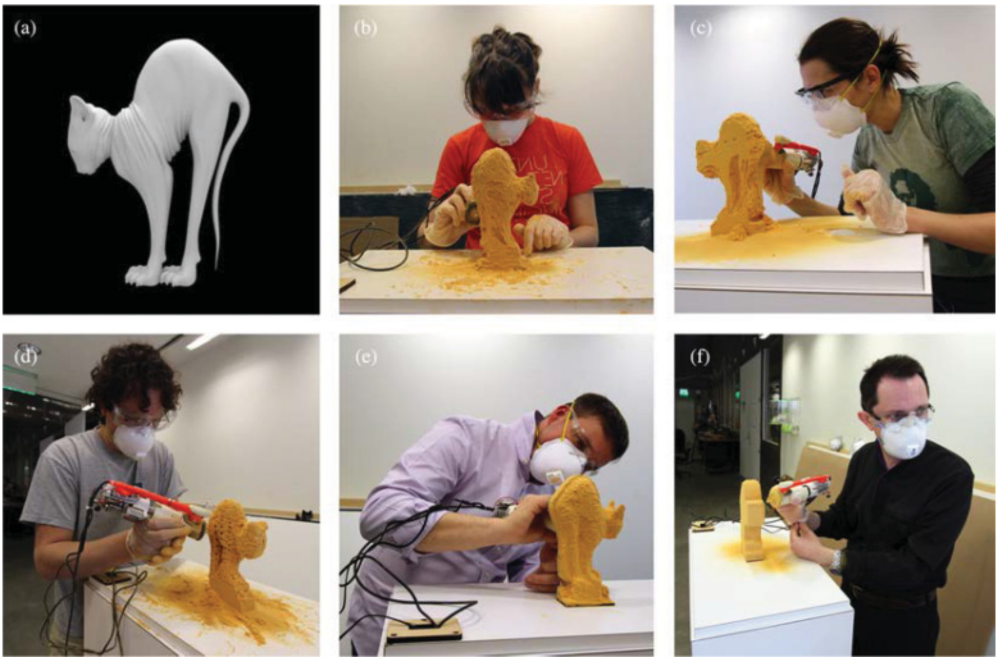


Fig. 12. (a) 3D model of a cat the participants were given to fabricate. (b) Jennifer, (c) Tamar, (d) Santiago, (e) Peter, and (f) Marco using the FreeD to make their own cats.

object, removing material from one side to another. As the model became recognizable, the operation changed to tracking the surface manifolds. Changes in spindle speed, when the bit approached the model surface, informed the users on the relative location of the tool with respect to the model and helped to inform their intuition. On the screen, a virtual mark represents the current position of the FreeD's milling bit. Occasionally, users relied on this mark in the initial stage before the virtual shape was revealed in the raw material.

6.4.1. Drawing a 3D Cat: Jennifer Jacobs.

> *It was a big revelation for me when I realized that I could use programming to draw (I wonder) what about programming makes it a useful tool for generating aesthetics?* — Jennifer Jacobs

Jennifer (28), a PhD student in the MIT Media Lab, has bachelor and master's degrees in the arts of drawing and animation but no prior background in carving. In her own research, she is developing tools to combine programming with digital fabrication, enabling the merging of art and design in a novel way to shape creative output.

Jennifer used the FreeD for almost 2 hours in making the cat model (Figure 13(a)). Following the fabrication process, she admitted she wouldn't have been able to accomplish this project without digital assistance. As a developer of design and fabrication tools, Jennifer used the tool as an enabler of design personalization, driving the tool to modify the cat's surface while depending on its guidance. For her, the FreeD served different purposes as she learned how to effectively use the tool: "The more you use it, you less rely on the tool as a feedback mechanism and override it." She added that she treated the FreeD like a drawing instrument.

Jennifer is used to thinking about sets of lines when illustrating, a thought process that is evident in many of her works (Figure 14(a)). She reinterpreted the cat design

Fig. 13. (a–e) Five cats made by five participants using the FreeD, all using the same CAD model. For each participant, we add an example of prior art.

in a way that resembled her illustration aesthetic, where lines are used as a way to transverse the composition (see Figure 13(a)). Looking at her final cat creation, this linear style is particularly evident in the detailed face, structural bone, and muscles she added to the original design.

6.4.2. Smoothing for Contrast: Tamar Rucham. Prior to working as a computer programmer for more than 5 years, Tamar (31) had mastered the crafts of silversmithing, goldsmithing, and blacksmithing, running her own practice. In making jewelry, she loved to search for shapes in abstract forms, and she developed a technique of heating silver until it melts in order to create amorphous structures (see Figure 13(b)). Never guided by a plan, she decides during the process how to use the output.

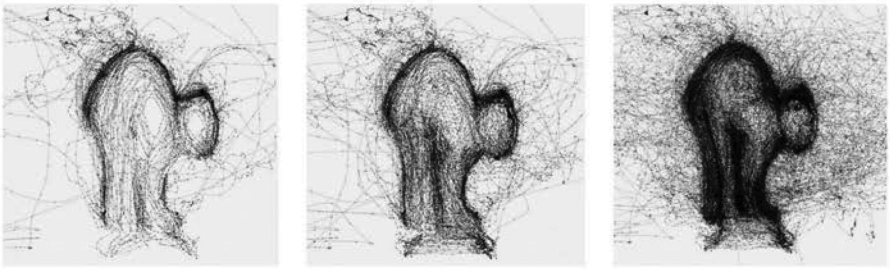
> *I like random processes, I like the unexpected and the surprises, letting life guide you. When you just copy things, there is not search. For me it was always about searching something inside the material a journey, not knowing its end.* —Tamar Rucham

Tamar's search for abstract forms evolved into an aesthetic of contrasts; her works reveal a dichotomy between the rough surface of the molten material and the smoothed areas where she sanded the material. This same duality appears in Tamar's cat, where she similarly sanded the cat's head and base. Tamar was unaware of the similarity of her cat and the style of her jewelry. Rather, she interpreted her action as a desire for details: "I wanted to go farther in smoothing what the tool can do..."

Unlike Jennifer, Tamar is skilled in figurative wax carving. She didn't force the tool to express her will, and she switched to a different technology when needed. She used the FreeD for 90 minutes and was the only user who used sandpaper, smoothing the face and base of the cat, and reintroducing the aesthetic she developed and deserted years ago.

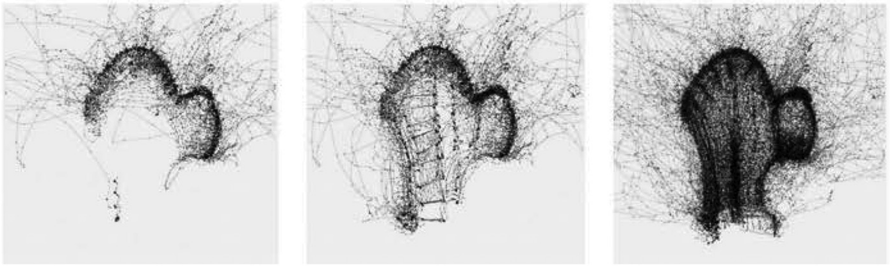
6.4.3. From Search to Pattern: Santiago Alfaro. Santiago (36), a product designer and a PhD student at the MIT Media Lab, developed a new working methodology with the FreeD, evolving into a radical design modification. His technique with the FreeD bears a strong similarity to his perspective on the formulation of manual practice.

(a) Jennifer

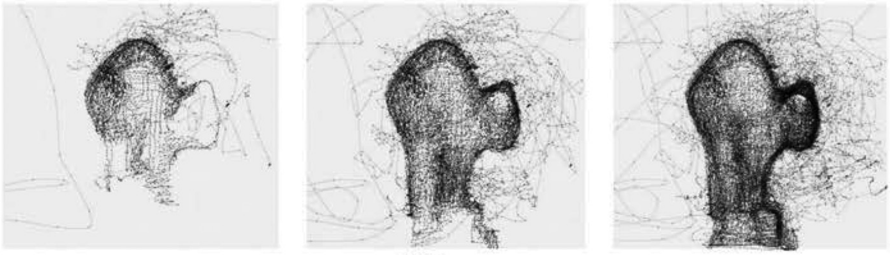


(b) Tamar

(c) Santiago



(d) Peter



(e) Marco

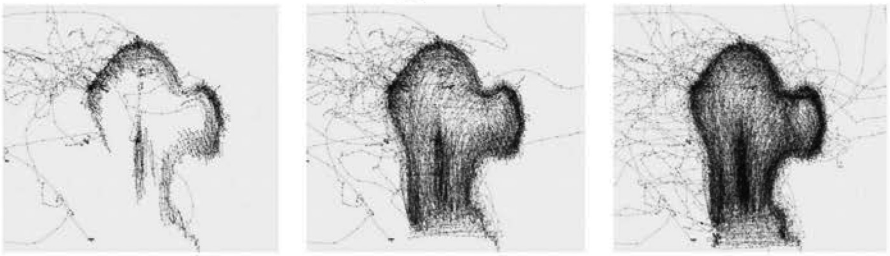


Fig. 14. (a–e) Tool-path visualization for each participant in three different stages of the work.

As an experienced practitioner of pottery and glass blowing, Santiago feels computer interfaces are too formulated. In his research, he seeks to design devices that interact with a broad range of human senses. Santiago prefers glass blowing to pottery because he feels pottery is too difficult to predict and requires a great deal of manual training. For him, the methodological procedure of glass blowing is compelling because it combines precision and control in material manipulation with a full-body tactile experience.

> *After I had to do a lot of coding, I understood that what I really like is the manual feel. I do find myself attracted more to the intuitive, hands-on experience than to everything that is computer based.* —Santiago Alfaro

Together with Jennifer, Santiago took longer to complete his model than all of the other participants (around 110 minutes). During this time, he experimented with many different carving techniques, searching for a method. Exploring what the tool could do, he poked the shape while studying the design. His methodology then evolved into drilling patterns of holes to expose the underlying model (see Figure 14(c)). Santiago tried to prevent accidental drills and, at the same time, deliberately used his drilling technique to make a pattern at the cat's back (see Figure 13(c)).

6.4.4. Dynamic, Static and Precise: Peter Schmitt, PhD. Unlike Santiago, who continuously searched for a method, the final two participants used the FreeD in a way that demonstrated their confidence in carving gained from many years of prior experience. Peter (35) is a mixed-media artist, trained as a traditional sculptor, but later specializing in digital fabrication, kinetic sculpting, and robotics.

As an artist, Peter is searching for dynamic and organic qualities in mechanical artifacts. He has developed printed gearboxes and clocks, laser cut servomotors (see Figure 13(d)), and milled bearing mechanisms that later provide the building blocks for more elaborate works of art. In all his mechanical designs, Peter expresses the tension between static and dynamic qualities of the machine, contrasting mechanical elements with static constraints such as containing cases.

The same tension appears in Peter's cat, where he decided to leave one half unfinished, contrasting the cat with its material origin. As a maker of CNC machines, Peter explained that he wished to reveal the process of making in the artifact. In the unfinished side of the cat Peter added a personal inscription, which read: "bioengineered cat for Amit." Peter invested almost 90 minutes in carefully milling the half cat. Having a lot of experience in both manual carving and mechanical fabrication, Peter used an organized tool path and creating a relatively accurate surface finish, with no special intention to override the surface.

6.4.5. Executing a Plan: Marco Coppiardi. Marco (45) was the last participant in the study: a violin-maker with 30 years of experience making top-end, hand-made violins, violas, and cellos using traditional tools and techniques. Marco is highly skilled in carving and would not normally require a tool like the FreeD to complete a model similar to the cat. He worked faster than all other participants, completing the cat in only 80 minutes (including more than 10-minute break), executing an accurate replica of the design (see Figure 13(e)).

Although it took him 10 years to master his craft, Marco doesn't have a special attachment for any specific tool. For him, the key to making a good instrument is in the way all the parts are perfectly assembled together.

> *(Today) working with a musician is more interesting than roughing and carving wood; it is about design, and fine-tuning the whole process in the beginning it was just about making the objects.* —Marco Coppiardi

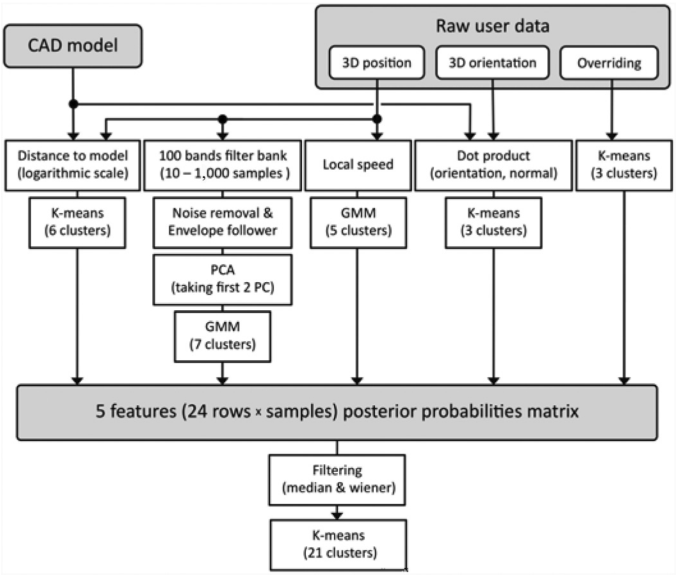


Fig. 15. Technique detection procedure: feature extraction and clustering process algorithm.

Marco does not object to the use of automatic machines (although he does not personally use them), assuming he can still refine the resulting instrument manually. Thus, for him, carving tools have no special value besides being a fabrication agent with a well-defined procedure that moves him one step closer to the final artifact. This perspective is seen in the way he worked with the FreeD, applying an organized tool path to remove material from one side to another, keeping the model's integrity with a well-defined technique (see Figure 14(e)).

6.5. Quantitative Evaluation

In the quantitative section of the study, we used statistical methods to extract identifying features from the recorded data, including a 6 DOF tool path (which corresponded to the milling bit position), tool orientation, and the value of the pressure sensor (overriding value). We assumed these features would sufficiently represent the working style of participants as they operated the device over time. Through several forms of computational analysis of this data (see Figure 15), we detected 21 modes of work (i.e., techniques) across all of the participants, and we created a series of visualizations containing the dominant techniques. These visualizations identify a unique working style for each participant. Assuming short time variants have a weak correlation with the high-level cognitive working approach, the data are analyzed in a higher level perspective, integrating 2.5 minutes in one window for the final visualization.

The data from all participants were processed together as a long series (with a frame rate of approximately eight frames per second), and features were selected using a clustering method, either K-Means variant or Gaussian Mixture Models (GMMs), depending on which method resulted in a better separation. The features' data were then filtered twice: first with a Median filter to remove local outliers and then with a Wiener filter to smooth the data while preserving significant variations. A posterior matrix of clusters probabilities was calculated for each time sample, before all the data were clustered again into 21 working techniques. In the remainder of this subsection, we describe the extraction of the five elementary data features, the techniques detection algorithm, and, finally, an analysis of the results.

It is important to note that, naturally, this type of evaluation is biased by the selection of the features and their preparation. Furthermore, focusing on the techniques of single participants, we may not be able to generalize to an overarching nature of using the FreeD. From comparative observation, on the other hand, we gained invaluable insight into the correlation of the higher level design intent of each of the participants and their low-level operation with the tool.

6.5.1. Distance. For each time sample, a distance D from the model is calculated as follows:

$$i_N = \mathrm{dsearchn}(M_M, P_N);\ \text{for } j = 1 : N,\ D_j = \left|M_{i(j)} - P_j\right|. \tag{5}$$

Where M is a vector of the CAD model vertexes, P is a vector of the tool-path position samples, dsearch() is a Matlab function that returns a vector of closest points in the first argument to the points in the second argument. The for loop builds a closest-point distance vector D with respect to points P. In order to improve the resolution near the object, we map the distance to a logarithmic scale (any value smaller than –5 is trimmed) before it is clustered, using a K-Means variant, to six groups:

$$LD_N = \log(D_N - \min(D_N) + \epsilon). \tag{6}$$

6.5.2. Spectral Pattern. To identify repetitive motion patterns, a few additional stages are required. Each axis is processed separately, through a filter bank of 100 bands, with window sizes that vary from 10 samples (a bit more than 1 second) to 1,000 samples (almost 2 minutes), implemented using Finite Impulse Response (FIR) filters. A noise threshold is used prior to an envelope follower for each spectral band. In the next stage, energy values of the three separate axes are summed together for each of the spectral bands, assuming the overall spectral operation of the tool is more important than the direction of this operation.

Having a matrix of 100 bands, 2D Median and Wiener filters smooth the data. We then use a Principal Component Analysis (PCA) to compress the data and simplifying the clustering process before selecting the first two components for GMMs clustering of seven segments.

6.5.3. Speed. The temporal speed feature S (see Equation (7)) is calculated as a local derivative of the position of the bit, filtered and then clustered to five groups by GMMs.

$$S_i = 0.5\sqrt{\left(\partial P_{i-1}\hat{x} + \partial P_{i-1}\hat{y} + \partial P_{i-1}\hat{z}\right)^2 + \left(\partial P_{i+1}\hat{x} + \partial P_{i+1}\hat{y} + \partial P_{i+1}\hat{z}\right)^2}. \tag{7}$$

6.5.4. Dot Product. The dot product indicates the tool's angle with respect to the object surface. Since the system operates with a mesh model, the model inherently contains information about vertex normals. This feature is extracted directly by calculating the dot product of the tool orientation vector with the vertex normal at the closest point (as explained in the Distance section) and then clustered using a K-Means variant to three clusters.

6.5.5. Overriding Value. Probably the simplest feature to extract, overriding values were calculated using the recorded FSR button pressure value in each time sample. Samples were clustered using a K-Means variant to three clusters, representing three major modes: no override, soft override, and a manual operation mode. Since the pressure value read from the FSR is less noisy than all previous data, representing relatively low-frequency user input, there was no need to smooth the data before clustering.

Fig. 16. Twenty-one different techniques (A–U), with Peter's tool path for demonstration, where the timeline is constructed by averaging over time windows of 2.5 minutes. The size of the bubbles represents the relative time in that state at a given time point, while the yellow mark represents the dominant technique.

6.5.6. Detecting the Participants' Working Techniques. The five features construct a 24-row matrix, at the length of 214,118 samples. This matrix represents the probability of a given sample belonging to each of the feature clusters. After PCA (to reduce the dimension of the matrix), the first nine principle components (preserving 90% of the matrix energy) are used for K-Means variant clustering. In order to determine the optimal amount of clusters, we used Silhouette Width Criterion, searching for the K with the maximal value. Iterating from 3 clusters to 50, the search converged to 21 clusters with the highest score.

The detected clusters represent 21 different working techniques (or states). Starting from an idle mode, through a variety of tool movements far from the objects surface, to different milling procedures and model penetration, we describe each of the states in Figure 16. A few examples are *Idle mode* (A), *Very slow movements far from work, mostly in or out of idle mode* (C), *Fast breaking off from milling while switching sides of the model* (G), *Careful repetitive milling movements close to the object, tool is parallel to objects surface* (Q), or *Slow penetration of the model* (T).

Figure 17 shows the results of the technique analysis for all participants and demonstrates a significant difference between each individual's techniques and his or her

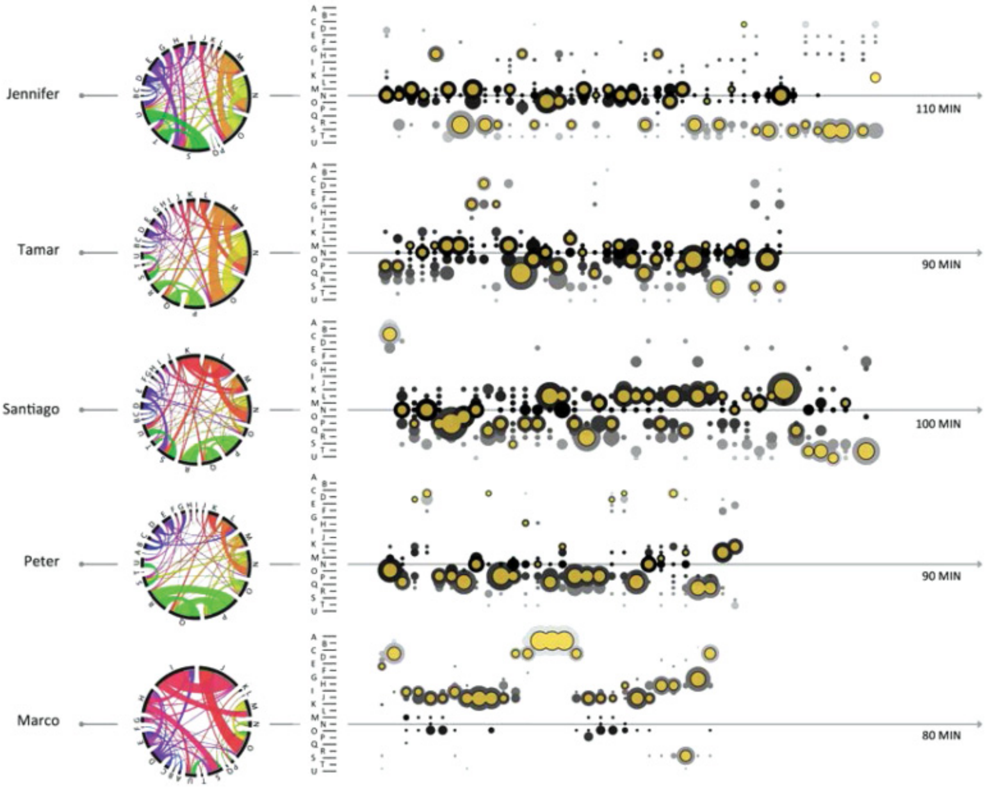


Fig. 17. The techniques detected for the five participants. Left: circular visualizations of the transition matrix between techniques, as a unique signature of the participants' work. The thickness of the connecting line is proportional to the number of transitions between these two states, while the colors are consistent between states of all users. Right: timeline of techniques with an averaging time window of 2.5 minutes.

style of work over time. The left side of the figure visualizes the transition matrix between states as a signature of the maker's style in this project. The right side represents the working procedure and use of techniques over time (integrating the data with a 2.5-minute time slot).

Overall, there was a correlation between the work techniques used and the carving experience of the participants. For example, Marco, the violin-maker, showed high levels of confidence and used a small number of work techniques, finishing the work faster than all other participants. Marco was also the only participant to take a long break during the work, "to let the hand rest." However, Santiago, who had never carved before, used the tool for a longer amount of time than Marco and switched between working techniques to search for the best style. This correlation supports the discussion in the next section, where we integrate all the data collected during the studies into a concluding discussion.

6.6. Discussion

Before focusing on the users' performance and experience, it may be useful to start with a summary of the participants' response to the functional properties of the tool. Several participants noted it took them a while to trust that the tool would prevent errors that would result in damage to the model. A few participants complained the tool was a bit too heavy (especially its backside where the motors are located), and that the handle was slightly too large for their hand. Moreover, several participants showed interest in replacing the current milling bit, which cannot be easily done with the current design. In addition, dust entering the bearing mechanism creates friction problems, requiring constant oiling of the ball bearings.

Overall, the tool did not exhibit major problems during the work, enabling the participants to continuously work in their own style while completing the model. Although we did not integrate the augmented reality system in the study, the participants did not complain about the lack of such a feature. Instead, they looked at the computer for visual reference when needed, developing tactile forms of carving intuition as opposed to relying on a visual interface.

6.6.1. Skills and Style. Each participant's style contains a different meaning. Jennifer and Santiago, the two participants who had no prior carving experience, needed more time to complete the work; however, they were still able to realize deeply personal interpretations of the model. Switching between many techniques and studying their interaction with the FreeD ("it is a new tool and deserves a new technique" —Santiago), their lack of experience evolved into an open-ended process, where the end results reflect their investigation.

For Santiago, using the tool was a learning process rather than a fabrication task. Therefore, he cared more about the experience, and less about the execution or result:

> *I really like the idea of NOT planning the reason I say that might be because, if I dont have enough skill to do EXACTLY what I want, then I can be happy with the end results.* —Santiago Alfaro

Jennifer's tool path corresponded to her professional opinion. She believes tools are not "one dimensional" and investigates multiple creative uses for any one tool. Developing hybrid fabrication tools for her own research, Jennifer noted, "the end products are useful to explain my work," hinting it may not be obvious to value the end products over the process itself. Jennifer internalized the FreeD as a tool allowing her to experience a process otherwise unreachable.

On the other extreme, Marco is a professional who carves in his daily practice. Working with the FreeD, he operated quickly and accurately, using a confident carving methodology. Marco's cat revealed the organized procedure he uses in his work, as a result of his technique, rather than an effort to personalize the output. When he makes violins, Marco uses many tools and technologies to finish the surface of an instrument, eliminating almost completely the rough tool marks from early stages.

> *If in one hundred years someone would like to do an exhibition of my instruments, they will all be different I am not interested in clones.* —Marco Coppiardi

Marco incorporates many different skills in his work: design, selection of materials, a variety of fabrication techniques, finishing, and acoustic fine-tuning. Thus, to our question "does the cat belong to me or to you?" Marco answered, "to you," since we selected the tool and model, and he only executed the rough stage of what he views as a larger process.

On the other hand, Peter and Tamar are both skilled in carving, having a few years of professional training, but currently do not practice the art. Together with Marco, they used the tool without pushing its envelope. Later, they commented on their desire to use different milling bits and modify the FreeD to suit their personal needs. However, unlike Marco, both Peter and Tamar interpreted and personalized the design. Unlike Santiago and Jennifer, Peter and Tamar refrained from using the FreeD to alter the cat's surface: Peter decided to leave half of the cat unfinished, while Tamar used sandpaper to refine a few details.

6.6.2. Attachment. Using the FreeD, Jennifer, Tamar, and Santiago put more attention and time in making the face of the cat. Moreover, for Peter, the face was the only part he completed from both sides. The figurative bias demonstrated in the milling patterns of the participants corresponds to human natural attention to faces.

Tamar and Jennifer expressed a strong interest in creating a figurative sculpture. Before she worked with the FreeD, Jennifer expressed interest in using the tool to do "generative modeling" (referring to her research in parametric design) or a figurative "human face." To the same question, Tamar answered "maybe some type of bird, or a dragonfly something that flies, since we like contrast, trying to get the balsa foam look light." Tamar's sandpaper technique was intended to convey this lightness. The sanding not only created a contrasting set of textures but also thinned the base, making the cat lighter and almost detached from the ground.

When we asked the participants to whom "does the final cat belong?" few participants answered "to you only" (Marco) or "to me and you" (Peter and Santiago). Conversely, Tamar shared ownership with the tool, describing it as an equal contributor to the making process. As she saw it, they both "danced" together to accomplish the work, allowing for a form of interactive interpretation that was based on intimacy rather then authority. Jennifer's objective on the question of ownership was more complex; she expressed deep attachment to the cat ("I love it!") but had difficulty separating the object from the larger making performance.

6.6.3. Narratives of Hybrid Interaction. While interviewing participants, we sought their perspective on the possible synergy between manual skills and computational capabilities. When we encouraged participants to conceptualize a futuristic studio where their fabrication vision could be realized, most of them described technological concepts. Peter however felt that the question was meaningless for him, and stated: "as an artist, you are a child of your time." The technical challenges of the present are Peters medium, and he finds it irrelevant to visualize far-fetched concepts.

All other participants shared visions of a computational environment, one that could better fulfill their present desires or needs. Their idealistic visions of future forms of fabrication shed light on what they currently find lacking in their daily practice. Marco, for example, finds himself investing too much time in noncreative labor activities. He does not worship the manual craft elements of his work, but instead emphasizes the importance of the complete creative process. Although Marco is responsible for the entire process of producing a violin, similar to a chef in a restaurant, he doesn't necessarily need to personally execute all of the technical stages of the work. It is difficult for him, however, to find an apprentice with a skill level that matches his own. He would therefore like to have a digital assistant, in the form of a suit with tracking devices, trackable tools, and a scanner to determine the condition of the work. Marco conceived of this system after using the FreeD, explaining that it could record his techniques and train a fabrication robot to replicate the skills of a master. Marco would use this robot to save time, guiding it during the process and checking the quality of the work at important stages. Despite his enthusiasm for incorporating digital fabrication into his practice, he explained that contemporary technologies are still far from his vision:

> *The CNC machine is still too remote...there is a need for connecting [technologically] to the body of the maker who uses the machine.* —Marco Coppiardi

Marco admitted that craft knowledge is gathered by hand, but he doesn't feel that manual practices should be maintained for nostalgic reasons alone. For him, working with a computer is a lot harder than making a violin, but he claims he would be satisfied with a successful result from either discipline. However, he is aware that in order to gain intuition for guiding the robotic system he describes, one would need to practice manual techniques for a long period of time ("it took me 10 years to master violin making"). While promising liberty for the master, Marco's vision doesn't consider the needs of the beginner.

Unlike Marco, Tamar sees handcraft as form of meditation, where tactile and manual involvement is crucial:

> *I like to do whatever it is that I want, and to let the material lead me; this is the whole point of the world, unexpected.* —Tamar Rucham

Reflecting on her experience with the FreeD, Tamar suggested a version in which the computer would generate random shapes, allowing her to investigate and search through the shapes as they emerged. Similar to Tamar's silver melting process, this leads her creative practice. The unpredictable qualities of craft give her joy because she believes that an artifact's singularity emerges through manual investigation and discovery. Although she is aware that her manual fixation may diminish if she practices craft for a long period of time, Tamar added that, as a computer programmer, she misses this open-ended, tangible experience. Unlike Marco's practice, where the goal is to create a perfect working instrument, Tamar is looking for the process itself, without any predefined target.

Santiago is also interested in open-ended investigations and seeks an intuitive tangible design process. While Tamar sees the experience of making artifacts as her goal, Santiago's FreeD experience made him reconsider the professional product design process, which usually involves starting with CAD and then engaging in physical prototyping. Instead, Santiago advocated for an opportunity to introduce an iterative dialog between physical prototyping and the computational design process, breaking the current order and allowing natural tactile engagement to influence digital design from the beginning.

The temporal and spatial qualities of the hybrid territory were discussed by a few of the participants as performance qualities. Jennifer, for example, claimed the computational records revealed different types of connections and forms of intimacy between the user, the FreeD (and its designer), and the product:

> *There is a lovely quality that makes both the implications (the manual experience and the produced artifact) and record (such as tool-path documentation) of an event visible, which are two different things to do.* —Jennifer Jacobs

The making experience made Jennifer rethink how involvement in the process creates uniqueness and how the computer can create a unique form of documentation of this singularity while it evolves (see Figure 18). Since the FreeD has limited influence on the CAD model, the fabrication process becomes the product of the work, and it is constantly changing. Jennifer is aware that the inherent nature of digital documentation makes it easy to reproduce a final product, independent of temporal or unique qualities. She stated that this disadvantage is overcome by the FreeD because the tool reintroduces temporality and uniqueness to the process.

6.7. Study Conclusion

The user study presented in this section sheds light on the process of learning to use a virtual tool such as the FreeD while also demonstrating how subjective interpretation can personalize the product. Correlation between personal narratives and the identity of the participants as makers can be observed even in quantitative measurements. This correlation, gained by engagement in the practice of making while facing challenges that appear during the work or of ideas evolving while using a carving tool, could not be realized before the fabrication process. This form of involvement allows for a

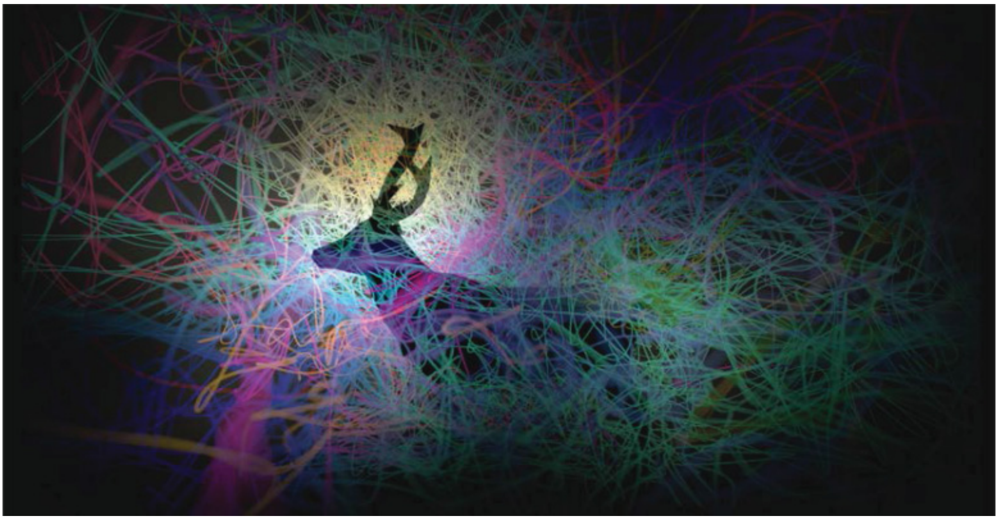


Fig. 18. **Documentation, or the creative work itself?** Combined (smoothed) tool-path visualization of six users working on the deer project. Each user is represented by a different color. After rendering by VRay, the output was processed in PhotoShop to intensify specific parts of the tool paths.

discussion of fabrication skills and design styles, qualities that are often absent in digital fabrication practices, which separate the stages of design and fabrication.

The user study supports our hypothesis that through tactile engagement during the creative process, makers introduce personal style that can impact the initial design. The study also contributed a few additional conclusions. There is a clear link between the personal identities of the makers and the quality of their products. Furthermore, each of the participants expected a different type of interaction with the tool. Postulating future work, we suggest that a hybrid interactive system will be beneficial for open-ended processes, allowing makers to define the amount of computational control they use. Beginners may need guidance to simply complete the task at hand while they develop their techniques as part of the investigation. A skilled maker, on the other hand, may require higher level control, allowing the computer to reproduce his or her skills or, alternatively, manually seek different objectives, such as introducing random qualities to the process, as in Tamar's meditative vision. The image of human–computer synergy is subjective and should be developed to be open-ended and variable if it is to support a real creative engagement.

7. SUMMARY

The FreeD is a novel contribution to the growing pool of digitally guided craft tools, allowing designers to engage with raw material in a new way and, at the same time, integrate 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. We propose a new technique in which digital capabilities integrated with hand-held carving tools assist inexperienced makers, as well as CAD designers, in carving complex 3D objects. The FreeD enables interpretation and modification of a virtual model while fabricating it, keeping the user's subjective tool path as a signature embedded in the texture of the physical artifact. Additionally, it is capable of completing tasks in a semiautomatic mode, generating a physical texture independently of the user. Because the FreeD allows for design manipulation to be integrated within a tangible carving experience, the nature of this work more closely resembles the process of traditional craft than other forms of digital fabrication while still allowing digital risk management and quality assurance.

We wish to enable creative work in a domain yet unexplored, a new hybrid territory of artifacts produced by both machine and man, fusing automated production with human subjectivity. Blending design with fabrication and automatic process with manual control, we believe the collaborative technology presented here has the potential to alter some of the dominant paradigms in contemporary digital fabrication processes. By introducing traditional approaches to the digital making of artifacts, we hope this intimate collaboration between people and computers will pave the path for a new type of interactions.

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