

D-Coil: A Hands-on Approach to Digital 3D Models Design

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ABSTRACT

We introduce D-Coil, a new digital 3D modeling approach using wax coiling to bring tangibility to the design of digital models. After defining a shape to extrude, the users follow the lead of a hand-held actuated extruder to instantiate the actual extrusion using wax. The tangibility of the wax extrusion sets the stage to create the next components until the digital model is completed. The digital model affords all digital attributes (ease of transformation, distribution, and 3D printing) while the wax artifact can be discarded or kept as a one-of-a-kind memento. We present a proof-of-concept implementation of D-Coil and showcase how this additive approach can also be extended to a subtractive process using a digitally actuated cutter. By adding a 6DOF mouse, users can also include scaling, rotation, and bending effects to create a wide variety of shapes often difficult for novices to produce in standard CAD software.

Author Keywords

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

ACM Classification Keywords

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

INTRODUCTION

As predicted by Gershenfeld [5], we have seen a rapid advance towards the democratization of 3D printing in recent years. One can draw a parallel with the rise of desktop printing in the 1980's [1], with one significant difference: it is still difficult to create complex digital models ready for 3D printing. Though the interface of CAD systems has been greatly improved, the learning curve remains steep and creating complicated, smooth shapes requires the mastery of complex construction commands (such as lofting between multiple contours using guide rails). Further, the isolation of the design and fabrication process in digital CAD software makes it difficult for all

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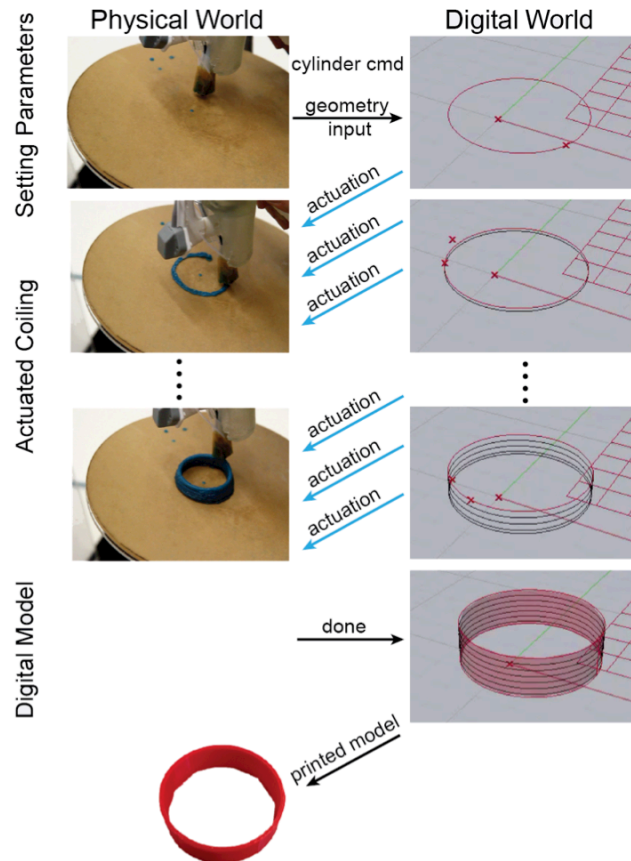


Figure 1: D-Coil concept: supporting 3D design using a wax proxy.

but experts to anticipate how a digital model will look and feel once it is built. This stands in sharp contrast with traditional craft activities such as clay coiling in which design and construction can occur at the same time. As observed by Schön [15], the intimate interaction between the designer and the material at hand establishes a constant reflective “conversation” promoting a faster convergence towards a satisfactory design. Clay coiling also has the advantage of being easy to learn for beginners (low floor), but offering sufficient flexibility to enable experts to create highly complex models (high ceiling) [13].

Several systems have proposed to bridge the gap between digital and hands-on building methods. Rivers et al.'s [14] proposed a hand-held, computer controlled 2D router to cut accurate shapes. FreeD V2 [25-27] offers a personalized rendering of an existing 3D model. Yet, none of these

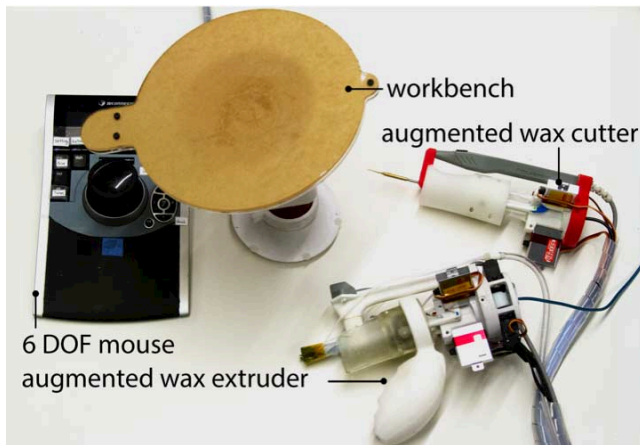


Figure 2: D-Coil system setting.

provides a hands-on experience for building 3D digital models from scratch. Others have focused more specifically on supporting model design. dePEND [21] supports users in creating accurate 2D drawings using pen actuation. Constructable [11] offers an interactive method for designing laser cut models directly on the laser cutter bed. Finally Cutter [19] instruments a hot wire cutter as input method for 3D model constructions. Both are limited in the scope of the models they can build.

We present D-Coil, a digital 3D modeling approach using wax coiling to bring tangibility to the design of digital models. As in standard CAD systems, digital models are designed by creating a succession of basic geometric primitives, but with D-Coil, additive construction takes place in the real physical world. For example, to build a cylinder (Figure 1), one would use the D-Coil tool as a pointer to define the center and diameter of a circle to serve as the cylinder base, then follow the lead of the actuated extrusion tool to coil up layers of an accurate physical version of the cylinder in wax. Because each geometric element is instantiated in wax as it is created, design and construction happen at the same time, providing explicit support for the reflective approach advocated by Schön [15]. This interaction greatly simplifies the conceptual model to be mastered for modeling because the wax model creates a natural reference for new additions to the digital model. Yet, the final output of the D-Coil design is *the digital model*, which affords all the benefits of the digital world such as ease of modification, distribution and replication (e.g., through 3D printing). The wax model meanwhile can be discarded, recycled, or kept as a memento of the design process.

We present a proof-of-concept implementation of D-Coil and illustrate how this basic creation cycle can accommodate subtractive operations using a computer actuated cutting tool. We also show how the basic extrusion method could be extended to create complex geometric shapes. To do so, we let users scale, translate, rotate, or change the orientation of the 2D profile from one layer to the next using a 6DOF mouse operated by the non-

dominant hand (Figure 2). Finally we illustrate how segmenting single contour 2D profiles into independent sub-contours further enhances the expressiveness of our approach. These capabilities make the system attractive for both novices and experts, providing both with a more reflective approach to their design process.

We conclude by presenting the limitations of the current system and discuss possible extensions including tools to repair broken objects or create complex additions to existing artifacts in situ.

PREVIOUS WORK

The common 3D printing work cycle (designing the 3D model on a computer, printing, iterating) requires a high level of skill for all but the simplest models and is hampered by the isolation between the design and the slow production process. This is a long-standing problem and several solutions have been proposed to address it. One is to improve the interface of 3D modeling tools as exemplified by Teddy [7], Sketch [24], Sketch-Up [6], and more recently I♥Sketch [3] among others. Another is to create a more tangible interface for the construction process. For instance, Anderson et al.’s system [2] uses digital Lego blocks to support model construction. It offers a low floor but the use of rectangular blocks limits its expressiveness. Shen et al.’s system [16] uses the deformation of a foam proxy to drive construction, but still creates a high barrier between the creation process and the instantiation of an artifact. It is also possible to support 3D sketching in the real world through an augmented reality interface as suggested by Yee et al. [22] and Yuebo et al. [23]. D-Coil goes one step further by creating a tangible artifact reflecting the 3D model being built.

Digitally Supported Fabrication

Several previous projects explore digitally supported fabrication. Some improve the hands-on tooling experience with computer aided precision. For examples, Rivers et al.’s propose a digitally controlled 2D router [14] to improve cutting precision. FreeD V2 [25-27] use a handheld computer controlled milling tool to encourage users to create a personal rendering of a digital model. Others have focused on additive processes: Haptic Intelligentsia [8] provides real-time haptic feedback when creating the outline of an object with hot gun glue; Mataerial [9] uses a robotic arm to create 3D curves in free space with additive fabrication. However, none of these approaches empower users to create an accurate digital model from scratch.

3Doodler [20], a handheld additive fabrication tool, is also related to our work because it brings 3D construction into the real world. Unlike D-Coil, 3Doodler does not focus on creating a digital model and it requires skill to create accurate geometries. By actuating the extrusion mechanism, D-Coil can help users create accurate shapes with little or no experience (similar to what the dePEND system [21] offered in 2 dimensions). Like Constructable [11], D-Coil is promoting a more direct relationship

between digital and physical construction. While Constructable focuses on models suitable for laser cutting, D-Coil extends the concept to a more general 3D modeler with a hands-on interface. To some extent, D-Coil represents a generalization of the Cutter system proposed by Willis et al. [19] but to a much wider range of designs.

ModelCraft [17], finally, allows users to modify 3D models by combining annotations with a set of pen-based commands, but the modifications are virtual until a new 3D print is executed.

D-COIL DESIGN

The main design goal of D-Coil is to add a hands-on building experience to 3D digital model design. Coiling is well-suited to this aim as it is easy to learn yet very expressive. However, creating accurate shapes while coiling requires practice. It would be counterproductive to simply sample the movement of the extruding tool as this would lead to poor digital models. To address this problem, our system is designed around a dialog between the user and an actuated tool. As shown in Figure 1, to design 3D geometry, the user first defines the digital base shape using the tool as a 3D pointer. In turn, this information is used by the system to create a digital model and control the actuated extrusion mechanism to create the same shape in wax. As the user creates more layers in wax, the height of the digital model is adjusted accordingly. Once the extrusion reaches the appropriate height, the user simply stops extruding and enters the parameters for the next primitive to be created. The same principle applies to substantive operations using a heated blade. At each step, the instantiation of the digital model in wax makes it easier for users to specify the geometric context necessary to proceed with the design. Yet, the main output of the process is a digital model that is easy to scale or otherwise modify, distribute, and replicate using a 3D printer. The one-off wax model is only a memento of the design process. In the rest of this section, we present our implementation of a proof-of-concept prototype of the D-Coil system. We then describe advanced construction methods in the next section.

Wax Extruder

We used the FreeD V2 hardware design [26] as a starting point for our wax extruder, but replaced the milling tool with a customized wax extrusion mechanism described in more detail in the implementation section. As in FreeD V2, a 6D magnetic tracker which is attached to the backbone of the extruder is used to capture the location and orientation of the extruder head. This is used to capture user actions during the input phase and provides feedback to the actuation mechanism during extrusion.

We extended the capability of the FreeD V2 design (which only controls the back and forth motion of a milling tip) by introducing a reverse-kinematic model, which precisely controls the deposit of the wax in a 3D working volume. This feature is important because it leads users' hand

movements along the correct extrusion path. We illustrate in Figure 3 that our system enables user to follow an accurate path without visual feedback. We provide three extruding heads of various diameters (1.5mm, 2mm and 3mm) to adapt to different needs in terms of modeling resolution and extruding speed.

Workbench

During coiling, it is often useful to reorient the wax model - either for construction comfort or to limit the impact of gravity on the shape of the wax coil. To address this need, we designed a workbench with a swivel base (Figure 2). The workbench encapsulates the magnetic tracker source as a reference origin for tracking coordination. Note that the user does not need to understand the workings of this coordinate system to successfully use D-Coil.

Building a Simple Extrusion

We use the process of a simple tube extrusion as a running example to illustrate D-Coil's basic interaction cycle (Figure 1). As in CAD systems, the process starts with the user defining the design base plane by using the extrusion tool to input 3 points. The user then inputs the shape to be extruded. For example, to define a circle, two data points are assigned on both the center and the periphery. Each time a data point is provided, the system extrudes a small dot of wax as a visual reference to help users construct the very first layer. The system offers other geometric shapes such as rectangle, ellipse, polygon as well as free hand drawing using the extrusion tip.

With the base profile defined, the system is ready for extrusion. During this phase, the actuation mechanism helps the user creating an accurate extrusion in wax. Extrusion will start as soon as the extrusion head is within reach of the path. From there the tool will "lead" the user to move forward along the path. The user simply needs to follow the extruding head movement so it is always in the center of the actuation range. This approach alleviates the need for an auxiliary digital display that may cause distraction from design activity. Once a given layer is finished, the system will automatically guide the user to build the next layer by raising the extrusion plane up one



Figure 3: Left model is extruded with actuated mechanism, right model is extruded with pure hand movement.

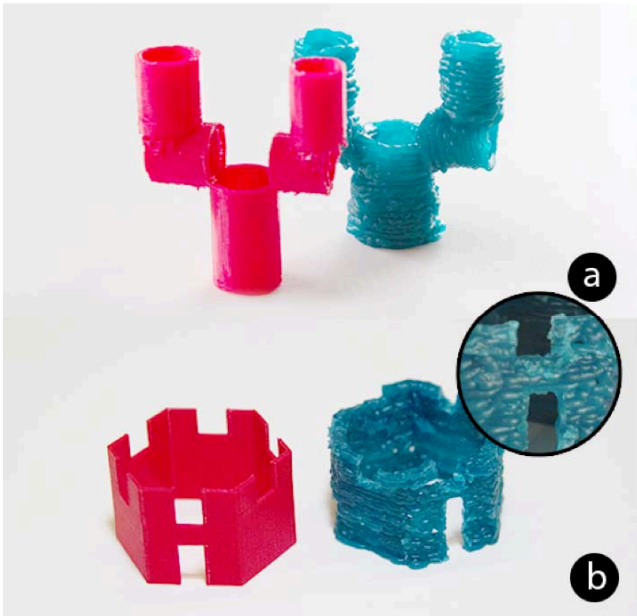


Figure 4: (a) A candlestick with multiple 3D geometries, (b) A castle with gate and ramparts created using wax cutter.

layer height. The model is created one layer at a time until the user decides to stop extrusion by simply moving the extruder away. Once the first extrusion is completed, the user can choose to add a new part to the model by simply extruding on top of an existing part. Our workbench design makes it easy to reorient the piece for comfort. Figure 4a shows a candlestick as a compound model example.

Cutter, Cut, and Undo

D-Coil also includes an actuated wax cutting tool as the subtractive counterpart of the extruder (Figure 2). We first considered using FreeD V2 as our subtractive tool, but initial testing revealed that milling is not well-suited for wax. Instead, we opted for a heated blade system replacing the wax extruder. The wax cutter tip is heated up to melt the wax model where a cut is needed. Like the extruding tool, the cutting tool carries a 6D magnetic tracker and is very similar in use. For example, to create the gate in the model shown in Figure 4b, we defined the 2D cutting shape by pointing out two opposite corners of the gate rectangle directly on the model. We then moved the cutting tool close to the opening. With the same guiding mechanism as in the extruder, the cutting actuation guided the user to cut along the profile. Note that the wax cutter can also be used for simple undo operations to correct overextrusions.

BUILDING COMPLEX GEOMETRY

To create a complex geometry, we departed from the standard CAD tools' reliance on construction geometry (such as sweeping a contour along a path to create a tube or lofting successive contours to create complex shapes like the hull of a ship). The implicit, command-based nature of these features makes them ill-suited for a direct coiling approach. Instead, we revisited common clay coiling

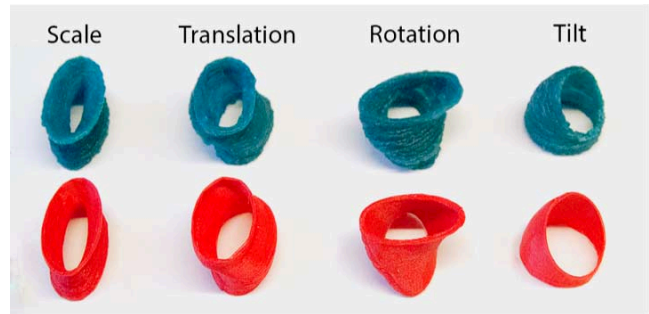


Figure 5: Transformation supported with 6DOF mouse.

practice and observed that craftsmen achieve complex 3D shapes by layering different 2D profiles on top of each other. For example, piling up 2D profiles with increasing diameter can create a tapered 3D shape and rotating 2D profiles along the same axis will form a twisted object. This inspired us to explore a fully explicit local control method to construct complex 3D models.

Controlling Geometric Transformation of a Coil

We first consider operations that do not modify the basic shape of the 2D base profile, including translation, rotation, scaling, and changing orientation. As shown in Figure 5, these transformations can create a wide variety of shapes when used in isolation or combined. Although the tool tracking system can be used to command such a transformation, we found that, in practice, it is much easier to use the 6DOF mouse (Figure 2) operated by the non-dominant hand to specify the required transformation. We use a direct mapping between the puck movement and the intended transformation with scaling achieved by pulling or pushing the puck. We opted for stepwise inputs to achieve better control and precision for the transformation. More specifically, translations are specified by 0.5mm increments, rotations by 10deg increments, and scaling by enlarging or shrinking by 1/100 of the current size. The user can get a sense of current profile location by observing the tool tip movement while operating the mouse. The tip will move towards the new profile to outline the new location.

The geometric transformations are easily translated into a new tool path with the exception of rotations around the X and Y axis, which result in changes in the orientation of the top layer. Such rotations are achieved by modulating the rate of extrusion along the coil to create a wedge by thickening the coil in certain sections (Figure 5 far right).

Editing the Coil Shape

So far, we have considered operations for which the basic coil shape is invariant. Such operations implicitly assume that, if a new 3D shape is needed, the user will create it by drawing new base 2D shape. In practice, there are occasions when the newly designed shape needs to be similar to the previous one. It will then be difficult and tedious for the user to reproduce the shape by tracing the contour. To address this problem, D-Coil offers two

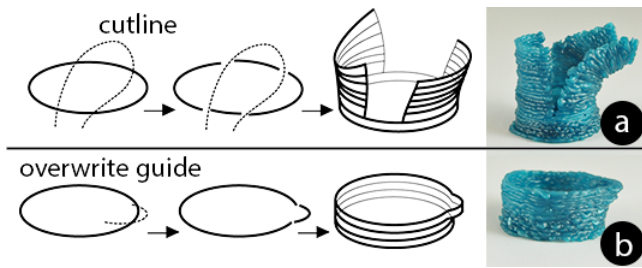


Figure 6: (a) Splitting a 2D profile and extruding each side. (b) Partially overriding a 2D profile.

primitives to transform the profile. The first is a split operation, which lets users split a coil into several independent segments. To split a 2D profile (Figure 6a), users press a split button with the non-dominant hand and draw a cutline with the extruder. The original 2D profile is replaced by several profiles, which can be operated on independently.

One can also override a profile (Figure 6b). Here, one selects the override command with the non-dominant hand and draws a path with the extruder. By default, the new profile will be integrated into the original profile, but it is also possible to have the system consider the addition as an independent profile. Figure 7 showcases the creation of a pitcher spout using this feature.

Copying and Pasting Geometry

One of the advantages of D-Coil compared to traditional craft techniques is that it enables fast replication of any part of a design using the digital 3D model as a template. This makes it possible to implement a copy-and-paste feature. To copy a part of a model, the user can hold down the copy button and move the extruder tip along the part of the model to be selected. All coils that are being crossed will be selected and placed on the clipboard. The model will be anchored at the selection point of the first coil being crossed. To paste the selected geometry, the user points the



Figure 7: Pitcher with spout. The spout is made using the overwrite function and the profile is considered independent from its original profile to achieve a taper shape separated from the main pitcher body.

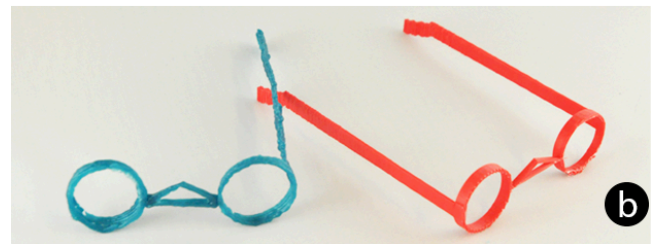
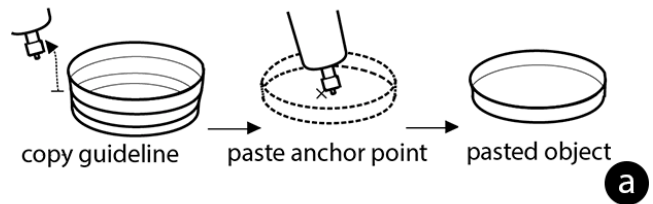


Figure 8: (a) Partially copy and paste of an extruded object. (b) Glasses made with the copy function. Both frames are made in the wax model, but the arm is pasted digitally without being instantiated. The printed model has both arms.

tool at the target location and presses the paste button. In our current implementation, the geometry will be replicated with the same orientation as the original model (Figure 8a). The user can then start to extrude the copied object. Note that our system does not require that all copies be instantiated physically. Figure 8b shows a pair of glasses where the replication function has been used to create two identical frames. In addition, one of the arms has been copied into the digital model without being instantiated in the wax model. Note that the printed glasses have both arms.

CREATING COMPLEX 3D MODELS

We now use a teapot example (Figure 9) to illustrate how we combine multiple functions introduced above for complex 3D modelling. We started by extruding a circle profile while scaling it to form the teapot body. We then used the cutting tool to cut a hole for the spout on the physical extrusion and added a spout combining scaling and bending operations. The handle was made via freehand drawing into the air. To compensate for gravity and



Figure 9: A completed teapot.

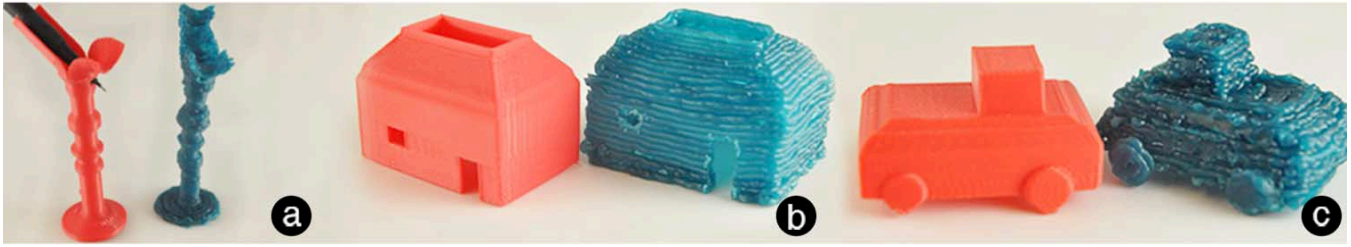


Figure 10: Various models created with the system: (a) Pen holder; (b) House with windows and doors; (c) Simple car.

sagging of the wax, we repositioned the workbench as needed during the construction. We show other examples in Figure 10.

Fitting a Model to an Existing Artifact

Using the free-hand drawing feature to start an extrusion, it is possible to create models that fit to complex surfaces. For example, one might want to add a crown or hat to a frog model (Figure 11a). To do so, one would use freeform drawing to create a path fit to the frog's head and extrude it following system guidance. If desired, one may flatten the top with another planar extrusion built up on the base shape with wax filling the small gap in between. Along with the wax model, a digital model featuring a good fit to the original frog is generated (Figure 11b). Note that such model fitting would be much more difficult in current CAD practice and would require scanning of the physical target surface, integrating this surface with the digital hat model, and printing to check fit and appearance. In the time it takes to design and print the crown once using the standard design cycle, a D-Coil user could explore several designs, getting immediate feedback on shape, location, and proportion.

IMPLEMENTATION

Our tools are partially based on the physical design of the FreeD V2 system [26]. We added a handle (Figure 2) to improve comfort and a new wax delivery system (Figure 12). The wax delivery was built using two rubber-gear

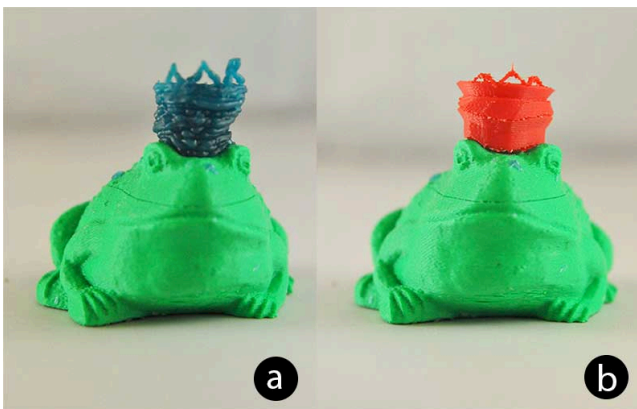


Figure 11: Fitting example. Frog prince wearing an add-on crown fitted to the head surface. The corresponding wax model is shown on the left, and the final design is shown on the right.

continuous servos oriented against each other to increase the grasp of the wax wire. We did not use teeth gear as in common 3D printers because wax is too soft for this approach. The extruder tip is custom printed in brass covered with two 5Ω/10w film power SMD resistors (PFC10) as heating elements and NTC thermistors (EPCOS B57540) attached for temperature monitoring. The extruder tip can heat up to 78°C within 1 minute and maintain the temperature while extruding at different speeds. At this temperature the wax is malleable but not liquid, and solidifies quickly after extrusion. To further speed up the solidification process, compressed air is blown on the extruded waxed using 4 jets located at the corners of the extrusion head. The cutter tip is modified from an off-the-shelf wax cutter (SJK Digital Wax Carving Pencil) with the same temperature setting as for the extruder.

Tracking (Polhemus Patriot) and actuation (MKS 6125 servos) hardware is adapted from FreeD V2 with a tracking source mounted inside a customized workbench. The 6DOF mouse communicates with the main program via UDP.

Software Implementation

The tool is based on a custom Grasshopper plug-in running inside Rhino CAD software (www.rhino3d.com). During the input phase of each interaction, the plug-in receives data from both the motion tracking system and the 6DOF mouse to update the model being created in Rhino. The digital model consists of a succession of 2D profiles, mapping the actual series of wax ribbons in the physical world (Figure 1). Digital models are updated automatically when the user starts a new layer. The current digital model is surface-based, a good match for our coiling system and

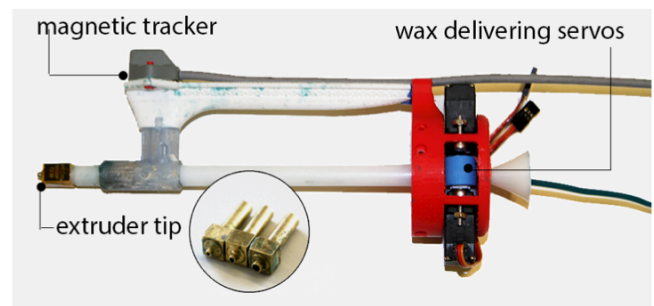


Figure 12: Extrusion system with wax delivery servos and printed brass extruder tips (several diameters shown). For clarity, the cooling system is not shown.

widely used in CAD software. However, our approach could easily be adapted to a volumetric modeler by applying shelling operations when needed.

During the extrusion phase, the extrusion and actuation is triggered when the tool head reaches the contour to be extruded. At this point, two things happen. First, the system initiates a feedback loop attempting to keep the position of the head fixed in space. This is done by sampling the position of the head at 30 Hz and using a reverse kinematic model to counterbalance any movement of the hand by adjusting the setting of each servo. This is not always successful because the user might move the tool too far away from the assigned position.

Second, we initiate active guiding along the contour. The system continually computes the position of a point on the path which is slightly (5% of the total length or the next path vertex) ahead of the current extruder position. The tip will physically lean towards the target point and thus lead the user to move along the path.

Our system also modulates the speed of the extrusion mechanism to reflect the actual speed of the user as well as any change in orientation required by user input. We also tabulate the completion level of each layer to decide when it is time to move to the next layer. A similar approach is used for the cutting tool.

DISCUSSION

We now discuss the lessons learned when designing the D-Coil prototype.

Coiling as Model Building Tool

The unique contribution of our system is to add tangible feedback and a reflective design experience to additive 3D digital modeling. We chose coiling as an interaction metaphor because it has a low conceptual barrier yet allows for the creation of fairly complex shapes. However, our approach also bears limitations and trade-offs like speed and expressiveness.

Design Speed

Though physical instantiation is not a fast process in general, our current prototype has attempted to solve this by introducing active guiding to “lead” the construction process and offering multi-size extruders to mass volume. We have anecdotal evidence that actuation itself could provide a 4-fold increase in speed when compared to an off-the-shelf wax extruder without augmented guidance (www.dumatt.com/Tools/tools.html). We believe that the speed could be further improved by refining the actuator design and the control loop of our system.

Yet, the reliance on bi-directional collaboration between user and computer introduces a fundamental upper speed limit. This is because the users must instantiate most elements of their design. This will become more noticeable when users become comfortable with implicit constructs familiar to expert CAD users. At that point, combining fast printing techniques such as WirePrint [12] with a CAD

system might offer a better solution. We believe that both techniques are complementary because they are serving different points on the skill continuum. We plan to compare the strengths of both techniques in future research.

Wax as a Building Material

We started our design with a clay extrusion tool. However, during preliminary tests, we discovered that the clay ribbon broke too easily during extrusion. Clay also takes a long time (about two hours) to fully dry, and is difficult to modify with a subtractive tool. We also considered plastic wire (ABS or PLA), one of the most common materials for desktop 3D printing and also used in 3Doodler. PLA and ABS set very quickly once extruded, but they are fairly rigid which poses challenges for the cutting/subtraction tools. We eventually chose GEO wax wire [4] because of its low melting point, fast cooling, and ease of cutting.

However, wax material has its own limitations. During our use of the D-Coil prototype, we discovered that the newly extruded wax might stay malleable for too long, leading to small offset or gaps (see Figure 13). This is, however, more of a visual aesthetic concern than a usability concern. First, our construction process is very robust to gaps in one layer. Users can fill up the gaps or simply coil over them at the next layer. More importantly, the digital model, not the wax model is the final outcome of the construction process. The wax model only provides scaffolding to support a reflective design process. In that respect, our construction method is sufficiently accurate for the intended purpose.

Of course the flexibility of wax could be beneficial as well. Inspired by art work by Henrik Menné [10], we imagine one kind of decorative design tool using dripping effects to add unique textures to a physical model while keeping its overall shape intact.

Expressiveness

Our main goal with D-Coil was to explore the feasibility of an extensive 3D modeling tool supporting reflective design. By combining both additive and subtractive tooling with local modification functions, D-Coil has demonstrated great expressiveness. However, the current version of D-Coil does not include implicit/command-based constructs. This is mostly because we believe that a purely explicit/direct tangible model design will be most suitable for novices and intermediate users. Our system, however, could be extended to a mixed paradigm. To support

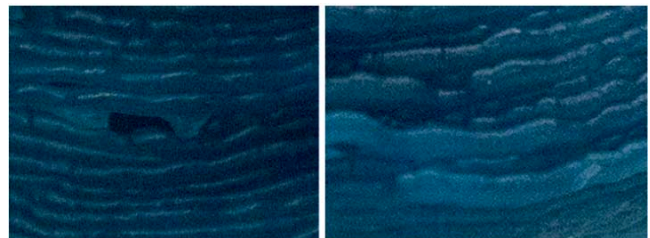


Figure 13: Imperfect extrusions. Left with a gap in one layer and right with wax offset.

implicit commands, we would need to provide a greater level of feedback in the context of the digital model so that users can place construction geometries (planes, virtual control points, etc.) and sketch accurately in the physical world. We would also need to provide visual feedback of the outcomes of implicit operations so that users can delay the start of the construction until they are satisfied with the outcome. Augmented reality glasses are one strategy to provide such feedback. Supporting implicit constructs would also require extending our extruding system to accept self-intersecting geometries which our current prototype does not support.

Model Accessibility

D-Coil adds tangibility to 3D digital modeling by creating a physical construction. However, tangibility will sometimes limit the accessibility of some parts of the model (inner structure), a problem that does not exist using a digital tool. In part, this could be addressed by careful planning, a common approach in constructing complex wax artifacts. Another approach is to simply destroy the parts of the model that are in the way since the wax model is just a proxy for the digital model. Empirical studies will be required to better understand how users react to this approach.

Incremental design

For the current version of D-Coil, we assumed that the model would not be detached from the workbench. This could be inconvenient when users would like to hold or reposition the object to get a sense of its fit. This could be addressed by creating a simple calibration procedure by which the system assists the users in creating 3 calibration marks using the cutting tools. After detaching the object and returning it to the platform, the users could calibrate the position and orientation of the new position by indicating the three reference points. This procedure could even be extended to situations in which the user already printed the object and would like to continue adding features on the 3D printout. The calibration feature would also allow for the creation of compound models from different parts.

FUTURE WORK

In this paper, we have focused on presenting the expressiveness of the D-Coil system. Next, we intend to implement a more robust version for broader deployment and evaluation with both novice and expert coilers. We would also like to explore whether the system can support more implicit constructs by extending it with various kinds of displays.

D-Coil as a Fixing Tool

We have shown in Figure 11 that the D-Coil system could be used to create models with a good fit to existing artifacts placed on the workbench platform. This feature could be extended to larger artifacts that may not fit to the platform by simply changing the tracking mechanism from a magnetic to an optical system (the simplest solution being

binocular cameras). After setting up the tracking system, users would define the origin of the working volume and start working. This approach would make it possible to create quick add-ons to existing objects or missing parts for broken objects (akin to a digital version of sugru [18], a clay-like compound that hardens to hard plastic).

CONCLUSION

In this paper we presented D-Coil, a digital modeling system using wax coiling to bring tangibility to the design process. Combining an extrusion tool, a cutting tool, and a 6DOF controller to control the coiling process, users can create a wide range of digital models often difficult to create in classic 3D design tools. We presented an implementation prototype illustrating how our approach can help novices to get started with modeling and can provide experts with a more reflective creation approach. We described the design and operation of the system and provided several examples illustrating its expressiveness. Once deployed, this system could let a broader range of potential users take full advantage of 3D printing.

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