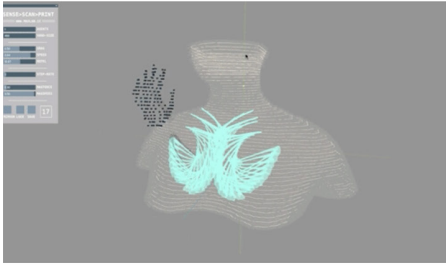


REVERBERATING ACROSS THE DIVIDE

BRIDGING VIRTUAL AND PHYSICAL CONTEXTS IN DIGITAL DESIGN AND FABRICATION

Madeline Gannon
Carnegie Mellon University



- 1 Reverb uses a gestural interface to 3D model on a point cloud (left). The form can be immediately exported for 3D printing (middle) and become integrated back into the scanned physical context (right).



- 2 Stills from Robert Hodgins's Body Dismorphia, 2010

ABSTRACT

Despite the increased fluency with digital design and fabrication in Architecture, our digital-physical workflows have yet to facilitate the kind of fluid experimentation and serendipitous discovery that is possible when engaging more traditional analog mediums. In order to bridge this analog/digital divide, we need to develop contextually aware *CAD/CAM* environments that (a) fluidly integrate physical context within virtual environments, (b) foster expressive interaction between a designer and design software, and (c) embed physical constraints of a fabrication process into digital geometry. This paper presents *Reverb*, a prototypical *CAD/CAM* interface for oscillating between digital bytes and physical atoms. The interface uses an integrated workflow (3D scanning, 3D modeling, and 3D printing) to enable a designer to craft intricate digital geometries around pre-existing physical contexts. The physical artifacts created with *Reverb* demonstrate how *CAD/CAM* interfaces can extend the creative capacity of a designer by integrating continuous tacit feedback from analog and virtual environments.

INTRODUCTION

Despite the increased fluency with digital design and fabrication in Architecture, our digital-physical workflows have yet to facilitate the kind of fluid experimentation and serendipitous discovery that is possible when engaging more traditional analog mediums. The many segmented operations that stitch Computer-Aided Design (CAD) to Computer-Aided Manufacturing (CAM) only emphasize the division between how one digitally *creates* and physically *realizes* a design (McCullough 1998). Although the intangibility of bytes and code inherently disconnects a designer from a material, the primary impediment to facile digital-physical workflows is our tools. They were not designed to explore the edges of the computational medium; they were created for automating technical tasks in *drafting* and *manufacturing*.

Ivan Sutherland's *Sketchpad* (1963) was not only the first Computer-Aided Design tool, many of its innovations remain integral to commercial CAD programs today. The graphical user interface (GUI), dynamic geometry, and object-oriented programming (OOP) were all developed on foundations that Sutherland built through *Sketchpad* (Buxton 2005). Likewise, the first Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) program, *UNISURF*, was developed by Pierre Bézier for the car company Renault in 1971. *UNISURF* was a modeling and path-planning software that converted surface-based designs into machine tooling operations (Bézier 1972). This model of CAD/CAM as a translator (from geometry to machine language) has remained largely unchanged for the past forty years.

Although developed over half a century ago, the legacy of *Sketchpad* and *UNISURF* remains ingrained in how CAD and CAM software are used today. The contexts in which we use these digital-physical workflows, however, have only diversified since the 1960s and 1970s. To support and encourage this diversity, CAD/CAM tools need to do more than just translate a digital design into a physical object; they need to be built with a contextual awareness of where and how they will be used (Willis 2011). This paper illustrates how contextually aware CAD/CAM environments can (a) fluidly integrate physical context within virtual environments, (b) foster expressive interaction between a designer and design software, and (c) embed physical constraints of a fabrication process into digital geometry. This paper also presents *Reverb*, a prototypical CAD/CAM interface for oscillating between digital bytes and physical atoms. The physical artifacts created with *Reverb* demonstrate how CAD/CAM interfaces can extend the creative capacity of a designer by integrating continuous tacit feedback from analog and virtual environments.

DIGITAL-PHYSICAL CONTEXTS

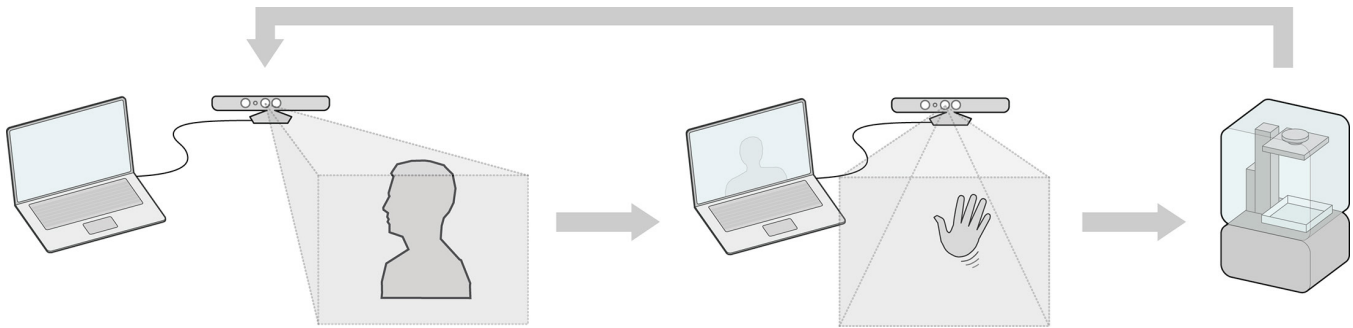
Reverb is a gestural software interface that fluidly integrates digital and physical contexts through a custom *chronomorphologic modeling* environment. The interface uses an integrated workflow (3D scanning, 3D modeling, and 3D printing) that uses a designer's real-world hand gestures to craft intricate digital geometries around pre-existing physical contexts (Figure 1). By coordinating complementary behaviors in 3D scanning and 3D printing, *Reverb* creates a closed loop for recursively designing imaginative digital forms that immediately integrate back into the built environment.

RELATED WORK

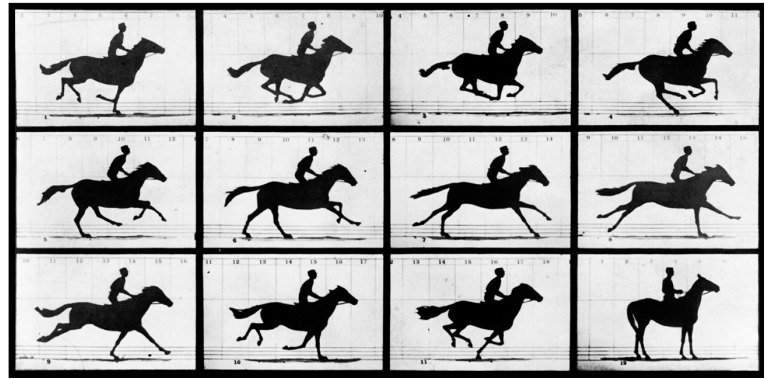
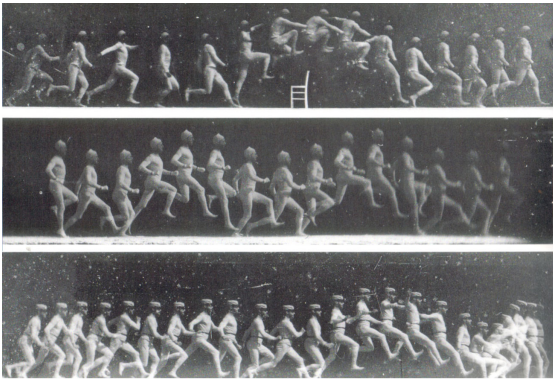
Gesture-based 3D modeling has primarily been explored through vision-based user interfaces. These interfaces rely on in-air interactions that are disconnected from a given physical context, and their output tends to be limited to either arbitrary, sculptural modeling (Gross 2001; Schkolne 2001; Llamas 2005; Sheng 2006; Zhang 2013) or to simple 3D navigation (Kim 2005; Wang 2011). Purposeful gesture-based 3D modeling can be achieved when interfaces incorporate physical context into their digital modeling workflows. *deForm* and *MixFab*, for example, integrate active 3D scanning of existing environments to facilitate 3D modeling for physical production. *Deform* combines malleable surface with physical props to give haptic feedback for 3D modeling (Follmer 2011) and *Mix-Fab* combines in-air gesture with physical props to create contextualized 3D models for 3D printing (Weichel 2014).

Similar techniques for capturing motion in gesture-based 3D modeling environments are also central to interactive and generative art techniques in new media arts. Golan Levin's *Merce's Isosurface*, for example, abstracts Merce Cunningham's *LOOPS* hand dance into finger and knuckle joints. The pure, raw data is then digitally reinterpreted as a system of undulating metaballs existing "in the liminal territory between pure abstract form and medical information visualization." (Levin 2009) Similarly, in Robert Hodgins's *Body Dysmorphia* (2010), the artist explores the inherent affordances of the point cloud as a computational material; Hodgins transforms the innocuous data from a depth camera into malformed, sometimes disturbing, self-portraits of himself and his cat (Figure 2).

The following interface for digital design and fabrication blends motion capture techniques in gestural user interface design and interactive, generative art to provide a framework for fluid experimentation between a physical canvas and digital form. *Reverb*'s digital-physical workflow enables designers to appropriate any physical context for their digital designs (Figure 3). 3D scans from depth camera data are used to translate a physical space or object into a point



3 Reverb's cyclical workflow digitizes a physical context via 3D scanning (left), enables 3D modeling around the scanned context (middle), and incorporates the form into the physical context via 3D printing (right)



4 Chronophotographic studies from Marey (left) and Muybridge (right)

cloud for the virtual environment. This point cloud is a persistent reference on which to base a digital design, and it gives a sense of scale to an otherwise empty virtual space. Once the physical context is integrated into the virtual environment, the same depth camera captures the designer's real-time hand gestures. These gestures interact with animate virtual agents within the chronomorphologic modeler. The expressive interaction between designer and virtual agent creates complex geometries around the point cloud of the physical context. These generated geometries are built around the physical constraints of 3D printing, and can therefore be instantly exported as valid, printable mesh. With the geometry crafted around the point cloud, the fabricated artifact is properly scaled for embedding back into the physical environment once 3D printed.

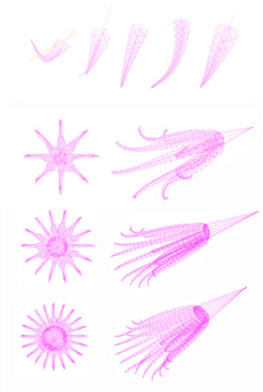
CHRONOMORPHOLOGIC MODELING

Chronomorphology—like its nineteenth century counterpart *chronophotography*—is a composite recording of an object's movement. In *chronophotography*, sequential photographs are captured from an object in motion. These stills are then separated into individual frames or collapsed into a single composite image. Étienne-Jules

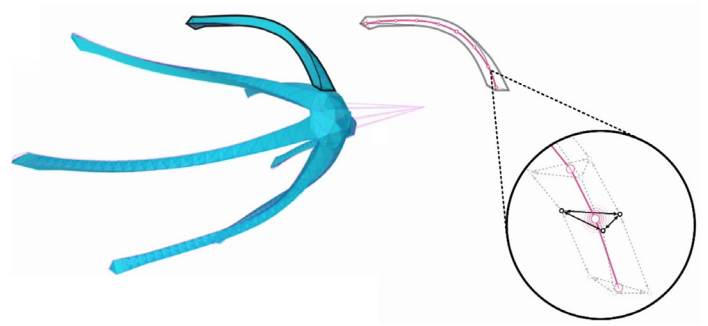
Marey and Eadweard Muybridge popularized this technique with their studies on human and animal movement. Their photographs revealed the true dynamism in which animate creatures carve through space and time (Figure 4). With *chronomorphology*, however, the recording medium is a full 3D model of a virtual agent simulated in a digital environment.

AGENT ANATOMY

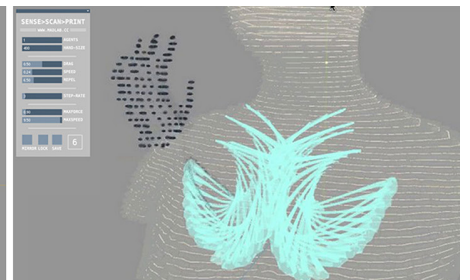
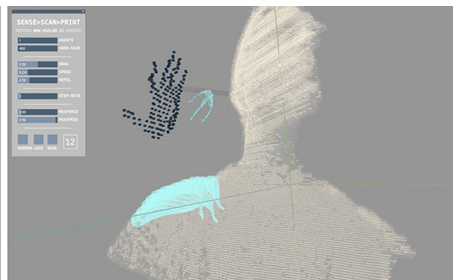
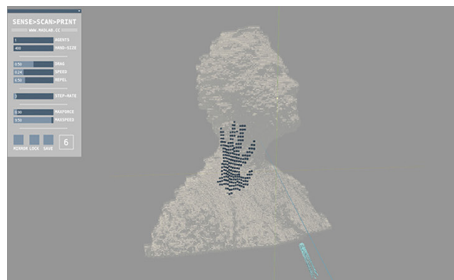
The virtual agent simulated within *Reverb* resembles a 'squid-like' form. While any animate 3D geometry can be used, the squid implementation provides ample parameters for exploring multiple variations of a single geometry. Its 'legs' are parametrically structured to have a range of options: from the profile and number of legs to its length and joint locations (Figure 5). As the designer guides the virtual agent through space and time, the composite *chronomorphologic* model leaves a trace of delicate lattices around the scanned physical context. This composite form, no matter how intricate or complex, is encoded with the physical constraints of 3D printing. Therefore, it will always be exported as a valid, printable mesh.



5 The virtual agent is parameterized to change (a) the length and joint locations within the legs, (b) the profile of the legs, and (c) the number of legs



6 The virtual agent's spring mesh ensures a printable geometry. Particles in the spine of the leg are weighted to create joint-like behaviors in the leg.



7 The point cloud actively repels the underlying particle system of the virtual agent. This allows the designer's hand to guide the agent directly on and around a scanned context.

To embed a contextual awareness of physical production into the virtual environment, the topological structure of the virtual agent was built as a soft-body spring model. In this structure, the edges of each mesh face are held together with springs, while the center is inflated with a spine of repelling particles (Figure 6). This system of particles and springs acts as an elastic skeleton that prevents self-intersections within the mesh, yet facilitates fluid motion. Moreover, a minimum wall thicknesses for *3D printing* was built into the parametric structure of the virtual agent's form. The resulting printable artifact, therefore, can push the material limits of a given printing process without breaking once fabricated.

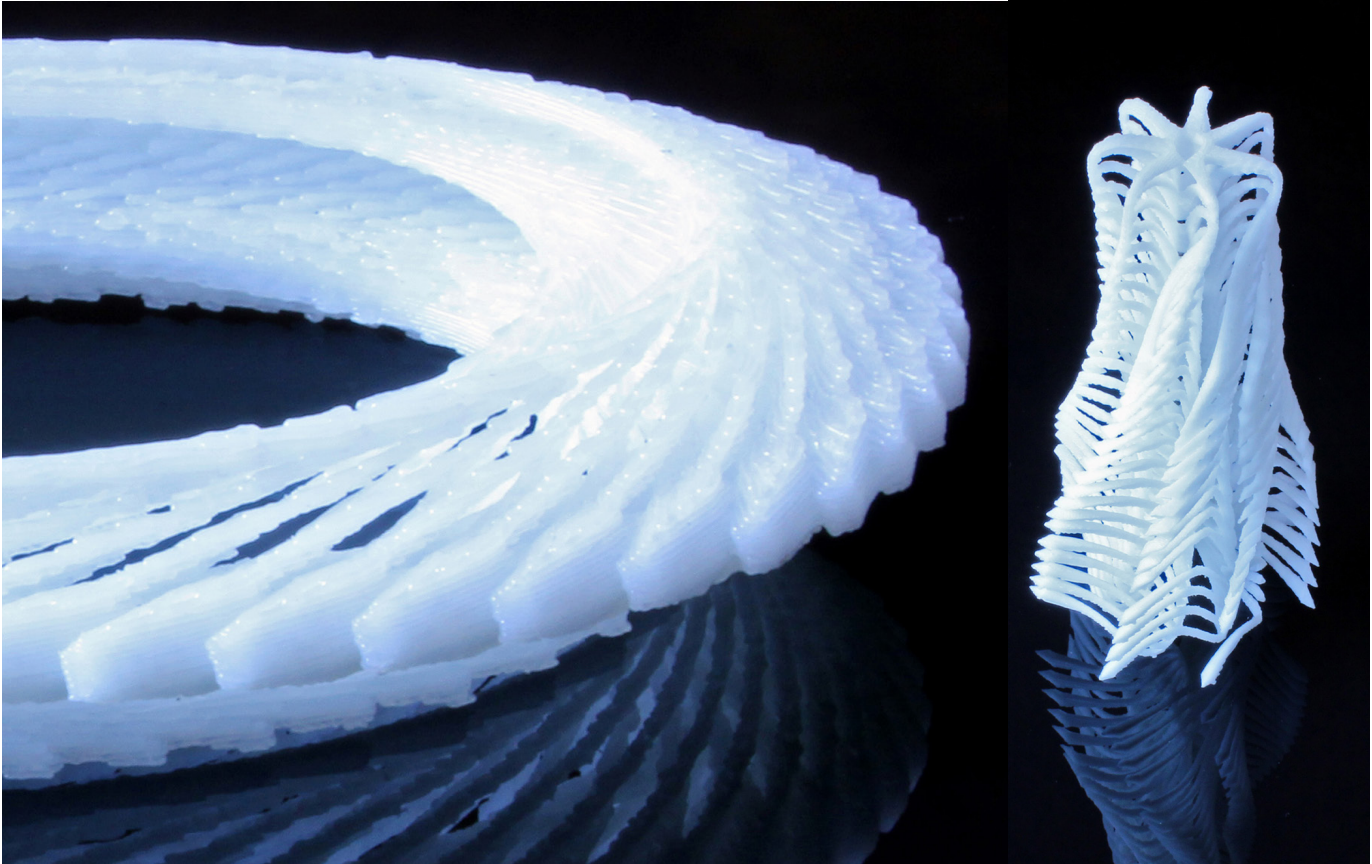
EXPRESSIVE INTERACTION

Rather than using a mouse or a keyboard to craft 3D form, the interface captures the designer's physical hand gestures. This act of bringing the hand into the virtual environment creates tacit interaction between the designer and the agent. There is continuous feedback between the movement of the hand and its influence when guiding the virtual agent around a scanned physical context. The geometry, then, is more than a module aggregated over space and time; it is a trace of a deeper relationship between the

virtual agent and physical hand negotiating one another. This intimate communication between hand and agent is a first step towards building contextual awareness across a virtual/physical divide.

The virtual environment also has variables encoded for modifying how the agent spatially responds to the hand. For example, the embedded point cloud actively repels the agent's particle system should the designer's gestures guide it too close (Figure 7). This prevents the digital geometry from intersecting with the scanned physical context, and ensures that the form will be appropriately scaled once 3D printed. Additionally, the designer can dynamically adjust the global physics variables simulated throughout the modeling environment. Through subtle changes in environmental parameters, the designer can create dynamic variation in the formal, material, and spatial qualities of a generated design.

The layers of encoded behaviors—in the virtual agent, the modeling environment, and the hand gestures—enable designers, regardless of technical skill, to rapidly craft baroque and expressive artifacts that both respond to and expand on existing physical contexts. The facile interaction between the hand and virtual



8 Initial prints testing the composite digital geometry

agent demonstrates how intricate, aesthetically striking forms can be arbitrarily easy to create. *Reverb*'s intuitive and expressive interface not only facilitates experimentation, but it also enables a designer to have continuous tacit feedback from directly manipulating the virtual environment.

PHYSICAL ARTIFACTS

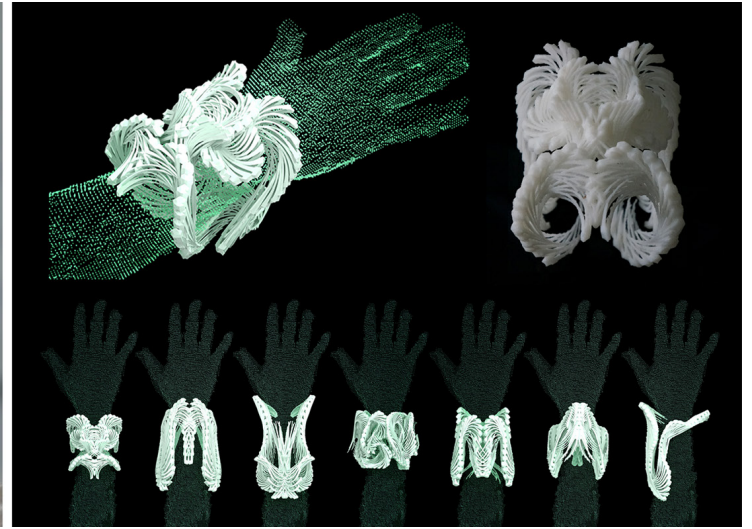
A number of artifacts were fabricated to test how well the physical constraints of a 3D printer were embedded into *Reverb*'s digital geometry.

Early experiments with *Fused Deposition Modeling (FDM)* printers and ABS plastic tested the topological structure of the composite chromomorphologic model. These prints verified that the single virtual agent would retain its printable properties without any boolean or post-processing operations (Figure 8). Later experiments tested the designer's ability to navigate around complex scans in the virtual environment. Three-dimensional scans of the arm were used as a freestanding canvas for crafting symmetrical and asymmetrical forms (Figure 9). A series of column studies

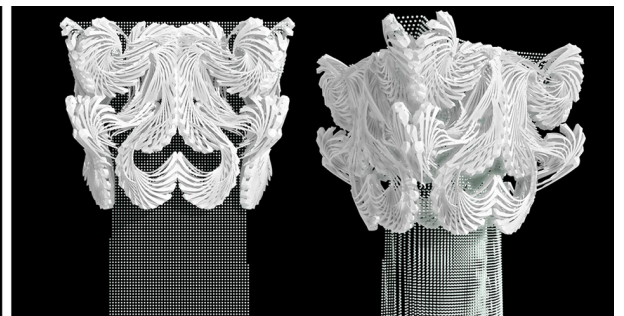
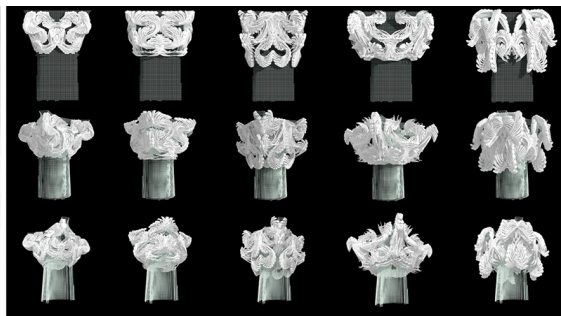
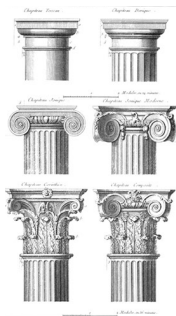
explored potential architectural applications: *Reverb* was used to create ornamental capitals over the façade of an existing Beaux-Arts building (Figure 10).

A final set of wearable prints was created via *Selective Laser Sintering (SLS)* from a scan of the bust. These pieces were a challenging test case for the workflow: As a virtual canvas, the point cloud of the neck, shoulders, and chest combined the formal complexities of the column scans with the navigational complexities of the arm scans. Moreover, as wearable objects, the design of the prints incorporated several ergonomic constraints for how the grotesque geometry met the body.

Although each collar was digitally designed in seconds, the resulting physical artifacts exhibit an amount of specificity and control when meeting the body (Figure 11). The way in which they neatly wrap the shoulder or delicately touch the nape of the neck demonstrates the benefits of using physical context to drive digital design. However, the expressive interface also enables a designer to craft spatial designs that diverge from their physical



9 A series of wrist studies were created to test symmetrical and asymmetrical configurations around a freestanding physical context



10 A series of ornamental column capitals were designed to augment an existing Beaux-Arts façade. These column studies tested the limitations of resolution and fidelity within the interface.

context. By balancing how the interface negotiates scanned context with dynamic interaction, the printed collars seem to converge and diverge from the body as anatomical extensions of the clavicle or sternum (Figure 12).

DISCUSSION

While *Reverb* has been tested with desktop or commercial *FDM* and *SLS* 3D printers, it has yet to be used with other additive manufacturing processes, such as *Sterolithography (SLA)* and *Direct Metal Sintering (DMS)*. Currently it is unknown whether the physical constraints of these additional output devices are properly embedded within the chronomorphologic modeling environment.

Reverb is not a comprehensive application for all processes in *Computer-Aided Design* and *Computer-Aided Manufacturing*; its use is far more limited than *CAD* and *CAM* software that is commercially available today. Further developments for the interface

would integrate modules for generating alternative animate agents within the digital-physical workflow. These modules would parameterize the formal and behavioral qualities of the virtual agents, and allow for expanded interactions with the designer. However, despite its constrained focus on additive processes in digital fabrication, *Reverb* speaks towards a larger vision for how our design and fabrication interfaces can better facilitate digital creativity to enter the tangible world. Its expressive gestural interface illustrates a number of useful affordances that conventional *CAD/CAM* software lack:

First, the interface embeds the technique of an experienced fabricator into the virtual environment; it generates and optimizes the digital geometry for physical production, so designers can focus their attention on what they are crafting in the virtual environment.

Secondly, there is a minimal learning curve for the software: like a physical material, the interface provides continuous tacit feedback between the designer's hand



11 The front (top) and back (bottom) of the three printed collars. Collar01 and Collar02 are made from rigid nylon, and Collar03 is made from a soft elastomer.

and the virtual agent. The responsive nature of the interface provokes the designer to discover the inherent possibilities of the virtual environment.

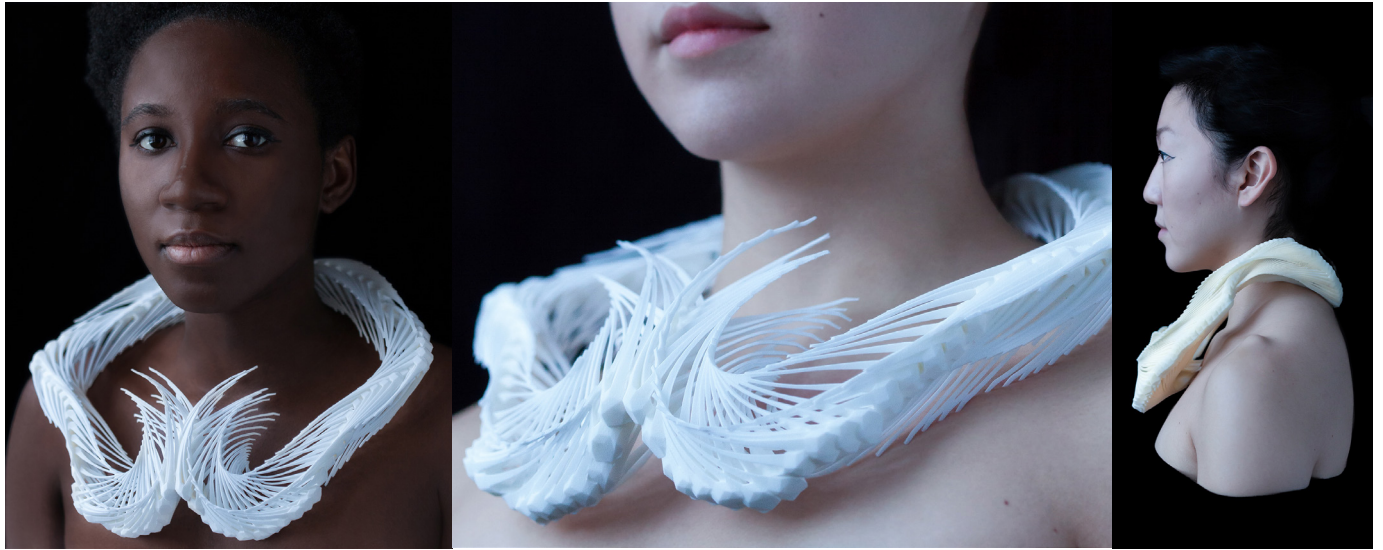
Lastly, the interface acts as a collaborator in the design process, and is not just a tool for executing a design; the layers encode behaviors between the virtual agent, the modeling environment, and the designer's hand gestures. Each have a certain influence, or agency, over the final formal outcome. By relinquishing total control over the virtual environment, the designer gains the capacity for serendipitous discoveries throughout the design process.

CONCLUSION

Reverb provides one prototype for bridging analog and virtual contexts in CAD/CAM workflows. By integrating environmental sensing within interactive interfaces, it illustrates ways for digital tools to have expressive influence over a design. The artifacts produced through *Reverb* also demonstrate how these tools can be imbued with the contexts of physical production: from the scale and form of a built environment, to the inherent limitations of an output machine. While more robust and universal tools are necessary, as a prototype *Reverb* effectively outlines key ingredients for narrowing the gap between digital and physical creativity.

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12 The printed collars converge and diverge from the body as anatomical extensions of the clavicle or sternum.

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IMAGE CREDITS

Figure 1. Gannon, Madeline (2014) Reverb Overview.

Figure 2. Hodgins, Robert (2010) Body Dismorphia.

Figure 3. Gannon, Madeline (2014) Reverb Digital-Physical Workflow Overview.

Figure 4. Gannon, Madeline (2014) Chronophotography Composite

Figure 5. Gannon, Madeline (2014) Agent Parameters.

Figure 6. Gannon, Madeline (2014) Agent Anatomy.

Figure 7. Gannon, Madeline (2014) Reverb Screenshots.

Figure 8. Gannon, Madeline (2014) Squid Prints.

Figure 9. Gannon, Madeline (2014) Reverb Wrist Studies.

Figure 10. Gannon, Madeline (2014) Reverb Column Studies.

Figure 11. Gannon, Madeline (2014) Reverb Collar Pieces.

Figure 12. Gannon, Madeline (2014) Reverb Collar Details.

MADELINE GANNON is a researcher/designer/educator whose work merges disciplinary knowledge from architecture, robotics, computer science, human-computer interaction, and design. Her research explores how the edges of digital creativity can integrate into the physical world. Gannon is currently pursuing a PhD in Computational Design from Carnegie Mellon University. She also holds a Masters of Science of Computational Design from Carnegie Mellon University, and Masters of Architecture from Florida International University.