ChronoFab: Fabricating Motion

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Figure 1: We bring the stylized motion visualization techniques of 2D pictures into the physical world of 3D printed models. Motion sculptures crafted with our tool from 3D animated objects explicitly visualize objects' motion in static artifacts

ABSTRACT
We present ChronoFab, a 3D modeling tool to craft *motion sculptures*, tangible representations of 3D animated models, visualizing an object's motion with static, transient, ephemeral visuals that are left behind. Our tool casts 3D modeling as a dynamic art-form by employing 3D animation and dynamic simulation for the modeling of *motion sculptures*. Our work is inspired by the rich history of stylized motion depiction techniques in existing 3D motion sculptures and 2D comic art. Based on a survey of such techniques, we present an interface that enables users to rapidly explore and craft a variety of static 3D motion depiction techniques, including *motion lines*, *multiple stroboscopic stamps*, *sweeps* and *particle systems*, using a 3D animated object as input. In a set of professional and non-professional usage sessions, ChronoFab was found to be a superior tool for the authoring of motion sculptures, compared to traditional 3D modeling workflows, reducing task completion times by 79%.

Author Keywords
Motion sculpture; fabrication; animation.

ACM Classification Keywords
H.5.2. Information interfaces and presentation: User Interfaces – Graphical Interface.

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INTRODUCTION
"*In sculpture, therefore, we are not necessarily looking for pure form, but for pure plastic rhythm, not the construction of an object, but the construction of an object's action.*"

-Futurist art movement manifestos, 1909 [14]

3D design and digital fabrication is gaining popularity among researchers and makers for rapid prototyping and designing a wide range of artifacts - including toys, jewelry, miniature figurines, mechanical parts and prosthetics. In general, such static, moving [6, 7, 33, 36], or interactive [24, 25, 35] 3D printed artifacts do not reflect movement over time. In contrast, a number of sculptors and artists have explored the notion of physically visualizing motion in static 3D sculptures (Figure 2), often adopting the styles and abstraction techniques used in 2D visual art which depict motion [8]. We refer to such artifacts as *motion sculptures*. Traditionally, sculpting motion sculptures manually- both physically and with digital tools - can be extremely tedious, requiring significant sculpting expertise and familiarity with fabrication constraints. In this paper, we present animation driven dynamic sculpting for *motion sculpture* form finding. By employing time, motion, and dynamic simulation, we explore fundamentally new workflows and ways of thinking for crafting 3D *motion sculptures*.

Psychologists and art historians have categorized the motion depiction techniques in 2D pictures [8, 16] and studied their emotional responses [8], which is a relatively mature form of expression. Compared to their 2D counterparts, motion sculptures are relatively less explored and have received little attention from the research community. To our knowledge, there is no catalog

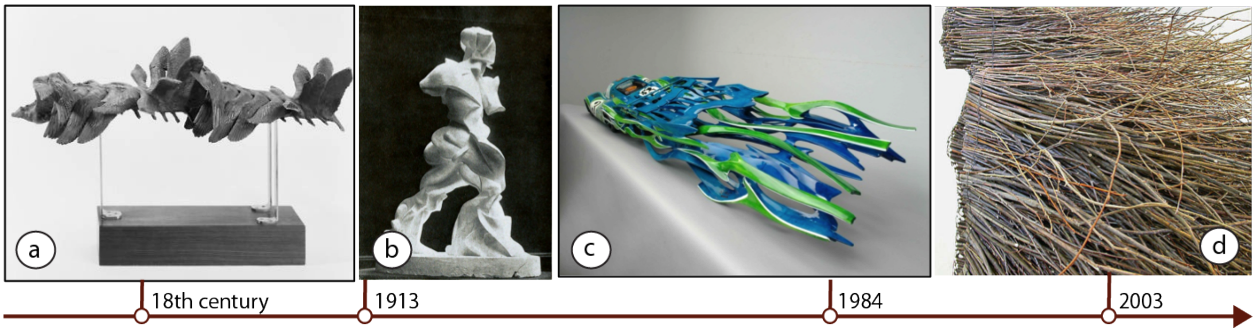

Figure 2. Motion sculpture as an art form has existed for centuries. a) Étienne-Jules Marey's bronze sculpture of a flying gull crafted from his photographic movement studies. b) Umberto Boccioni's sculpture (1913) of "Unique forms of continuity in space" is a notable example of the futurist art movement. Over the years, motion sculptures have become even more vivid and stylized, exploiting creative usage of colors and materials, as in work by Dennis Hoyt (c) and "Stillness in motion" by Olga Ziemska (d).

representing the styles and guidelines for depicting motion for static physical artifacts. We first catalog a list of existing 3D motion sculptures by a wide range of artists and explore the design space of motion depiction techniques. We then explore the materialization of motion into 3D printable geometric objects by employing the temporal dimension for the modeling of such sculptures. We then present ChronoFab, a novel system that allows users to craft motion sculptures, from 3D animated objects, that explicitly visualize objects' motion in static artifacts (Figure 1).The temporal dimension enables the use of motion (3D animation) and dynamic simulation (using Maya's[2] animation engine) as design tools for crafting static 3D forms that are otherwise complicated and tedious. Users can interactively generate and control geometric shapes of four different types of motion effects: *motion lines*, *sweeps*, *multiple stroboscopic stamps* and *particle systems*. The resulting artifacts can then be analyzed for structural strength and stability prior to their fabrication.

We conducted an initial evaluation of our system by having professional and non-professional artists work with both ChronoFab and traditional 3D modeling tools. Our results indicate that ChronoFab simplifies the creation of motion sculptures by intelligently utilizing the motion data to generate the geometries. Overall, task completion times were reduced by 79%, encouraging rapid exploration. We showcase a few resulting artifacts modeled by the authors and the participants which illustrate the expressiveness, ease of usage, and variety of applications of our system.

RELATED WORK

Design and Fabrication

Driven by the increasing availability of 3D printers and laser cutters, HCI and graphic researchers have taken a recent interest in the topic of digital fabrication – including the fabrication of interactive objects, functional mechanical assemblies and data sculptures.

For fabricating interactive objects, researchers have explored a variety of display and sensing techniques, including the use of 3D printed light pipes [35], computer vision to track the movement of interior components [24] and routing pipes through the interior of 3D models [25].

Researchers have also explored the design and fabrication of functional mechanical assemblies that mimic the behavior of an animation. Mechanical toys [36], humanoid motion capture sequences [6] and mechanical characters [7, 33] have all been digitally fabricated. These works optimize the assembly of mechanical components that best approximate the input motion after fabrication. Taking a deformable character and a set of poses as input, the design and fabrication of actuated deformable characters have also been explored [29]. While these works focus on the fabrication of mechanical assembly and actuated objects to reproduce an animation, our work represents motion sculptures, a unique form of art and expression to physically visualize motion within static 3D artifacts.

Helping amateurs for personalized design and fabrication is gaining interest in the computer graphics community. For rapid prototyping, Constructable [18] is a drafting table enabling users to interact by drafting directly on the work piece using a hand-held laser pointer. Other interactive research systems enable non-experts to design plush-toys [17] and personalized chairs [23]. We present an interactive system that enables non-experts to design and explore motion sculptures, using a 3D animated model as input.

Researchers have studied the efficiency of data sculptures [11] for physically visualizing information, and developed tools for fabricating data-driven physical charts [31]. Dragicevic et al. created a curated list of active and passive physical visualizations [9] to motivate and inform the design space of data-driven physical visualization. The vocabulary of the stylized motion effects in our tool is guided by a similar curated list of existing 3D motion sculptures which we contribute.

Motion effects in 2D pictures and 3D rendering

A number of tools and techniques have been developed for generating motion effects in 2D pictures and animation. Among all techniques, photographic blur has received significant attention from the computer graphics community. Sung et al. [30] developed a taxonomy of motion blur approaches and reformulated these approaches in a consistent mathematical framework. Teramoto et al. [32] built a system that enables users to generate a variety of motion effects from a single photograph. Such motion effects have also been used in the context of 2D user interfaces, as an alternative to animated transitions [4].

Researchers in non-photorealistic rendering have explored generating motion effects from 3D animations in the context of real time computer games [10], post-processing operations [12, 15] and programmable shaders [26]. Niehhaus et al. [20] presented a system to generate dynamic glyphs in a 3D scene, guided by scene specifications and user-directed expressions. While these examples serve as inspiration, our work aims to generate motion effects that can be fabricated and viewed from all angles, imposing very different requirements. Furthermore, we provide an interface that enables users to explore a variety of stylized motion effects, without requiring expertise in 3D animation, sculpting or scripting.

BACKGROUND AND DESIGN SPACE

Artists and scientists have crafted a wide range of motion sculptures to visualize motion, for various purposes ranging from aesthetic to analytical (scientific study of motion). To guide our design and explore the variety of motion depiction techniques, we review and categorize motion visualization techniques from our curated list of 3D motion sculptures and installations[1]. We also consulted with motion sculpture artists to gain insight about their existing processes and needs. While prior literature has categorized and discussed a variety of 2D representation styles [8, 16], to our knowledge, no such attempts have been made for 3D motion sculptures.

Motion Depiction Techniques in 3D

Physical 3D sculptures are fundamentally different from graphical 2D content, as the physical objects are tangible and subject to physical forces. However, we have found that many of the motion depiction techniques in 3D sculptures are analogous to the motion depiction techniques commonly used in 2D pictures and cartoons [8, 16]. We have catalogued 79 motion sculptures by 47 distinct artists or entities from art magazines, art history books, film production documentaries, and toy figurines. Taken all together, we identified the following four major types of motion depiction techniques in these artifacts.

Multiple Stroboscopic Stamps

Multiple stroboscopic stamps are commonly used to depict complex motion occurring within a very short period of time. The effect uses a series of discrete, static, slightly different 3D stamps of an object (or parts of an object) taken at different time intervals, overlapped into a single artifact (Figure 3). Depending on how it is utilized, this technique can be effective for portraying the impression of motion without sacrificing clarity or resolution of the moving object. Thus, this technique is used when the object is deforming over time, such as human movements or a flying bird. For scientific purposes, it can facilitate comparison of structure across multiple instances. *Multiple stroboscopic stamps* are commonly used in pictures (Figure 3a), paintings [8] and comics [16]. We identified 22 artifacts by 12 artists using this technique in our catalog.

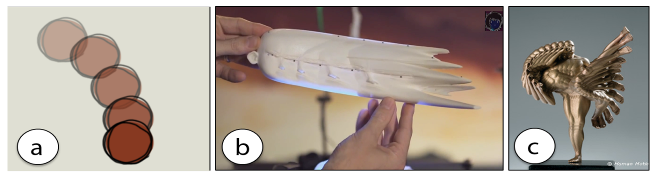

Figure 3: *Multiple stroboscopic stamps* used in (a) photograph (b), 3D printed artifact used in Studio Laika's animated feature film "Paranorman", and (c) Peter Jansen's human motion sculptures.

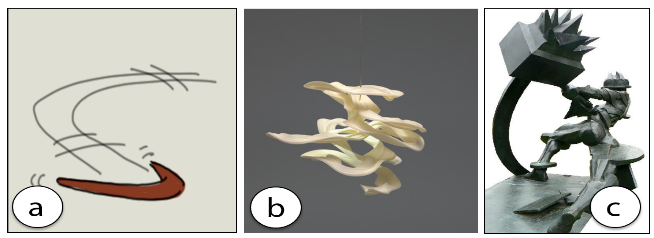

Figure 4: *Sweep* used in (a) comic art, (b) "*Attracted to Light*" by Geoffry Mann, narrating the behavior of a moth flying, and (c) "*Emotions in Motion*" by Michael Sandle

Figure 5: Examples of *motion lines* used in (a) 2D illustration, (b) a wire art ceiling installation by Teressa Leung, and (c) recycled animal art by Sayaka Ganz

Figure 6: Particle systems to depict motion used in (a) comics, (b) "What you see might not be real" by Chen Wenling, and (c) "Nuclear bomb" by Eyal Gever

Sweep

The *sweep* technique generates geometry by sampling numerous instances of a 2D *curve* attached to the surface of an object over a range of time (Figure 4). An analogous effect in 2D pictures is a long exposure photographic blur.

[1] www.autodeskresearch.com/projects/chronofab

Such effects are also common in comics [16] (Figure 4a). We identified *sweep* effects in 19 artifacts by 11 artists.

Motion Lines

Motion lines, also known as speed lines, are generated by sampling numerous instances of a *point* within an object over time to compute the trajectory of that point in space (Figure 5). *Motion lines* are used in cartoons, comics and scientific illustrations to represent the path of a moving object. In motion sculptures, artists sculpt 3D geometry along the trajectory of the *motion line*. We identified this technique in 22 motion sculptures by 15 distinct artists. Similar to comic art, we also identified stylized variations of *motion lines*, such as the use of turbulence (Figure 2d) and tethering (Figure 5c).

Particle Systems

Particle systems, such as smoke and fluid effects, are also used in motion sculptures to depict motion and trajectories (Figure 6). Such effects are also common in comics and illustrations, showing trails of moving objects, such as horses, bikes or rockets (Figure 6a). In the sculpture "*What you see might not be real*" (Figure 6b), geometric shapes of smoke are used to depict the motion of a bull. This technique was used in 8 artifacts by 4 artists in our catalog.

Observations and Discussion

Appropriateness of Techniques

Each of the described techniques has their own advantages and disadvantages [8]. *Motion lines* and *sweeps* are useful for representing abstract motion over a period of time. In contrast, *multiple stroboscopic stamps* and *particle systems* represent a snapshot of a state in time. The actual effectiveness of a technique can depend on the nature of the motion and artist's skill.

Color, Materials and Light

Common materials used to craft motion sculptures include bronze, metal, wires, wood, tree branches and even sand. Among all these motion sculptures, 23 artifacts by 6 distinct artists were multi-colored. We believe the recent advent in multi-material, colored 3D printers offer exciting design possibilities for fabricating these types of motion sculptures.

Uncategorized Techniques

In addition to the four main representation types discussed above, artists and sculptors have also developed a number of ad hoc stylized techniques to portray motion. For example, Umberto Boccioni's "*Unique forms of continuity in space (1913)*" depicts an aerodynamic and fluid form of a human in motion (Figure 2b). Such custom techniques can be very subjective, stylized and irregular which make it hard to formulate procedures for crafting these effects.

Change of parameters over time

We identified examples where artists change the geometric properties (parameters) of the motion geometries over time. For instance, in Figure 6b, the smoke particles spread out more over time. With the *motion lines* and *sweep*, geometries may become tethered (Figure 4c, Figure 5c) and more turbulent (Figure 2d) to represent the passage of time.

Figure 7: (a) Raphael Perret's "*Bodycloud*" uses multiple techniques together to portray motion (b) *Motion lines* in 2D can be difficult to represent and fabricate in 3D.

Automation in the Authoring Process

The majority of the reviewed motion sculptures were crafted manually. Several motion sculptures were aided by technology during their construction. In project "*BodyCloud*" (Figure 7a) and "*Human motion sculptures*" (Figure 3c), human movements were recorded by motion capture technologies and the final artifacts were generated with digital tools. However, in our correspondences, artists indicated that the process could be tedious and there was a desire for digital tools to enable rapid exploration.

"*To actually do it, took me about a year. Finding the process, getting access to the infrastructure, convincing people and getting the result*." –Raphael Perret.

Combination of styles

Artists often use a combination of physical representation styles working together to portray motion, similar to comic art [16]. For example, Raphael Perret's "*Bodycloud*" uses a combination of *multiple stroboscopic stamps* and *sweeps* to materialize the motion of human movements (Figure 7a).

Specific Considerations for 3D Fabricated Motion

Even though 2D pictures and 3D sculptures share many techniques for motion depiction, specific considerations must be taken into account when those motion depiction effects are being fabricated in 3D.

Structure Size and Stability

The 2D *motion lines* in Figure 7b are common in cartoons and drawings to provide a jittered appearance, but they may not be feasible in 3D due to their form factor. Unlike their 2D counterparts, 3D printed motion geometries are subject to fabrication constraints, such as minimum thickness and material strength.

Support Structures

Another important consideration is that objects in motion can often be positioned in mid-air. Without support structures, it is challenging to make it stable and balanced. Within our catalog, we identified sixteen examples where the motion geometries themselves also function as support structures (Figure 6b). Such motion geometries that also serve as support structures can assist in both the fabrication process and the balancing and support of the final object.

Summary

Our analysis indicates a rich design space and exciting possibilities to be explored in this art form. We also identified a number of stylized variations of the common motion depiction techniques, which are relatively less explored in previous computational tools. These case studies motivate us to design a tool that facilitates the creation and exploration of 3D motion sculptures.

CHRONOFAB

While many media artists and sculptures have attempted to depict motion in 3D sculptures and installations, there are no specialized interfaces or applications tailored for this purpose. As such, exploring and designing such forms can be tedious and difficult. In this section, we discuss ChronoFab, a new system we have developed, which enables users to model motion sculptures, using a 3D animated object as input. Users interactively author motion geometries by selecting components in the 3D model and adding a range of configurable motion depiction techniques. Once modeled, the resulting artifacts can be exported and prepared for 3D fabrication using existing tools.

Implementation

ChronoFab is implemented with MEL (Maya Embedded Language) scripting using the Maya [2] animation engine. The interface of ChronoFab is developed with QT, a C++ cross platform application and UI framework.

User Interface and Workflow

Our system uses the standard Maya viewport, timeline, selection and navigation tools (Figure 8). The interface has four main panels (Figure 9) for each of the motion depiction techniques – *motion line*, *sweep*, *multiple stroboscopic stamps* and *particle systems*. Within each tab, our interface offers stylized variation of effects for these techniques, with UI widgets for interactive controls.

The system takes an animated model as input. An expert user could use an animated model they designed, while a hobbyist could start with an existing 3D animated model.

The overall workflow to create motion effects is to first select a motion effect type, then specify a time interval, and finally, select a component (vertex, edge or the whole model) of the geometry to apply a desired effect to. The generated effects can be configured using their associated parameters in each tab of the interface. Figure 10 summarizes the overall workflow of the system with the example of a launching rocket.

In this example, the user first selects three vertices of the rocket (Figure 10b), and then generates the associated *motion lines* (Figure 10c). A *Tapered* style variation is then selected. The length of the motion line geometries is determined by the time slider interval, and the user can interactively control the radius and end points of the selected *motion lines*.

To generate a trail of smoke, the user specifies a vertex in the rocket (Figure 10d) and then generates a *particle system* (Figure 10e) which emanates from the selected vertex as it animates through the specified time interval. The user can then interactively control the *particle system* parameters to achieve the desired effect. Once finalized, the user converts the *particle system* into a polygon mesh (Figure 10f) and exports the model for fabrication (Figure 10g). Below we describe each technique in more detail.

Motion Lines

Motion line geometries originate from a point in the object geometry. Users can generate five stylized variations of *motion lines* (Figure 11) - *Cylinder*, *Tapered*, *Turbulent*, *Streak* and *Rugged*. The *Cylinder motion line* generates smooth volumetric curves along the trajectory of the vertex.

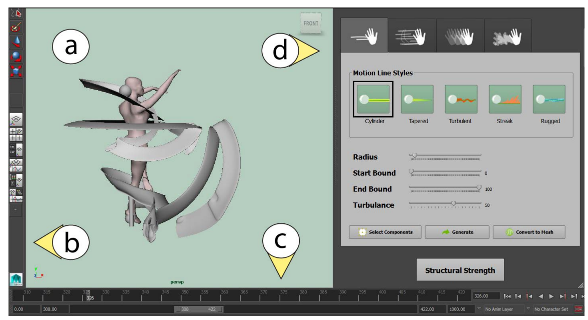

Figure 8: The user interface of ChronoFab is built in Maya (a) Maya viewport (b) Maya selection tool palette (c) Timeline slider (d) ChronoFab user interface.

Figure 9. The four ChronoFab effect panels each include parameters for stylizing their own effects (a) *Motion line* (b) *Sweep* (c) *Multiple stroboscopic stamps* (d) *Particle Systems.*

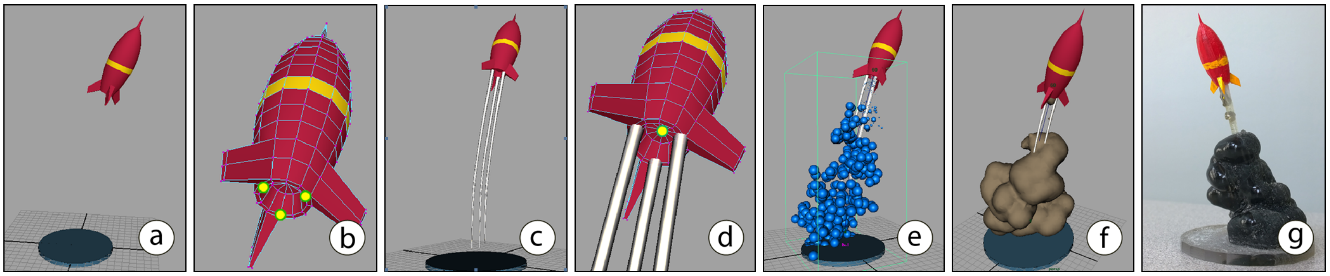

Figure 10: Workflow for crafting motion sculpture using an animated rocket as an input (a) The input animated rocket (b) The user selects multiple vertices (yellow) (b) The system generates *Tapered motion lines* from the selected vertices (d) Preparing to add a smoke trail, the user then selects a vertex (yellow) (e) The system generates a *particle system* emitting from the selected vertex (f) After iterative refinements, the user converts the *particle system* into polygon mesh (g) The 3D printed motion sculpture.

The *Tapered motion line* becomes thinner towards the end while the *Turbulent motion line* adds noise to the path. The *Streak motion line* generates gradually increasing sized motion geometries. The *Rugged motion line* is rough and irregular. To generate *motion line* geometry, the user selects the desired time interval and one or more vertices within the geometry. Pressing the "*Generate*" button creates *motion lines* in the user specified style and time interval.

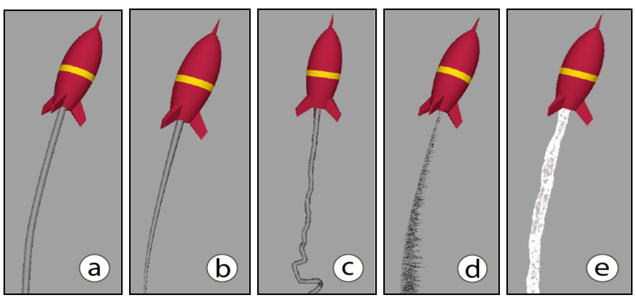

Figure 11: Five stylized variations of *motion line* generated (a) *Cylinder* (b) *Tapered* (c) *Turbulent* (d) *Streak* (e) *Rugged*

Our system computes the trajectory of the selected vertices in 3D space by sampling the target object location at discrete time steps. For *Cylinder*, *Tapered*, *Streak* and *Rugged*, we use existing Maya Paint Effects to generate geometries along the trajectory. For *Turbulent motion line* (Figure 11c), our system attaches a directional Maya Particle system with a point emitter to generate the *motion line*. A turbulence field is attached to the particle system to create the desired irregularities. A *radius* slider controls the thickness of the *motion lines*. The *Start bound* and *End bound* sliders control the starting and end clipping of the *motion line*. A *turbulence strength* slider controls the amount of deformation in the *Turbulent motion line*.

Sweep

Our interface provides three stylized variations of animated *sweeps* (Figure 12) – *Plane*, *Tapered* and *Turbulent*. The *Plane sweep* generates geometry along the trajectory of the 2D animated curve. The *Tapered sweep* becomes thinner towards the end while the *Turbulent sweep* adds geometry deformation over time. To generate a *sweep*, the user selects the time interval and desired *sweep* style. The user then specifies a 2D curve by selecting one or multiple adjacent polygon edges in the geometry surface. Pressing the "*Generate*" button constructs the sweep geometry.

Our system first connects the selected polygon edges to a 2D curve, attached to the surface of the animated object. Next we use Maya's "Animated Sweep" to generate a 2D surface from the animated curve. For a *Tapered sweep*, we linearly scale the animated 2D curve before generating the surface. Our system then extrudes all the polygon faces of the surface to create a volume with thickness for 3D printing. An *initial width scale* slider controls the minimum width of the *Tapered sweep*. The *Turbulent sweep* is implemented by attaching a particle system with a turbulence field to the 2D curve. Upon the generation of the *Turbulent sweep*, users can interactively control the *thickness* and *turbulence* of the geometry.

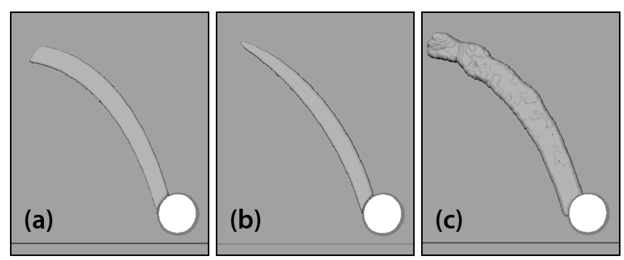

Figure 12: Types of *sweep* (a) *Plane* (b) *Tapered* (c) *Turbulent*

Multiple Stroboscopic Stamps

Users can create stamps of the animated 3D geometry at regular time intervals for a specified time range. There are two variations of this technique – *Plane* and *Scaled*. The *Plane* technique produces stamps without altering the scale of the stamps. The *Scaled* technique linearly scales the stamps over time.

We used Maya's "Animation snapshot" to generate the stamps. The *minimum scale* slider controls the minimum scale of the stamps. An *interval* slider sets the frequency of snapshots. Once generated, users can interactively control the stamp *interval* and *minimum scale* of the stamps.

Particle Systems

Particle systems are used to create smoke and fluid effects along a trajectory of a moving object. The user first switches to the corresponding tab and presses the "*Select component*" button. This switches the system to *vertex selection* mode. After selecting the desired vertex, the user presses "*Generate*" to generate the *particle system* (Figure 10e) along the trail of the selected vertex.

Our system creates and attaches an omni-directional Maya emitter to the selected vertex. A turbulence field is added to the *particle system* to induce irregularities in the motion of our particles. An underlying surface is created to collide with the particles and create a naturalistic smoke effect. Users can interactively control the *particle velocity*, *size* and *emission frequency*. For fluid effects, a fluid emitter is attached to the selected vertex of the object. Users can interactively control the *turbulence strength*. Pressing "*Convert to mesh*" converts the *particle system* into a polygon mesh to be fabricated.

Structural Strength Analysis

Users can often create structurally unsound shape that can easily break after 3D printing. In ChronoFab, users can interactively visualize and analyze the structural strength of the resulting artifacts by pressing the "*Structural Stability*" button. Our system uses Meshmixer [3] python API to visualize the strength of the 3D model through Meshmixer viewport (Figure 13) based on cross-sectional structural analysis that detects critical stress inside the 3D object [34]. In this view, any red coloring indicates structurally weak regions, which the users can then adjust to be thicker.

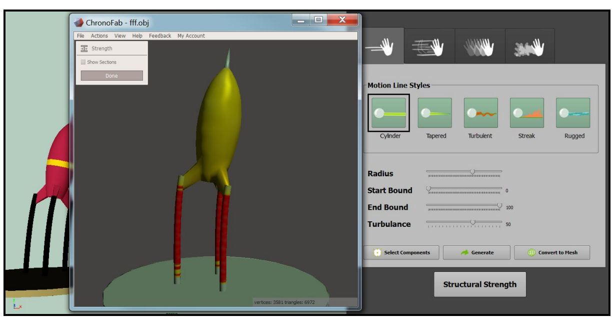

Figure 13: Visualization of the structural strength of a 3D model. Red color indicates structurally weak regions.

Fabrication and Results

Inspired by existing 3D motion sculptures, we used ChronoFab to test our system and fabricate a set of sample objects (Figure 14). We fabricated our models on a variety of 3D printers including the Stratasys Connex 260, Makerbot and ZPrinter 650. Some artifacts were hand-painted (e.g. Figure 10g) and some were printed in full color (Figure 1) and multi-material (Figure 14d).

Figure 14a depicts a creature throwing a tire, with stylized motion techniques inspired by comic books. The trails of the hand and tire are generated using the *sweep* function. In the bouncing ball example (Figure 14c), the motion

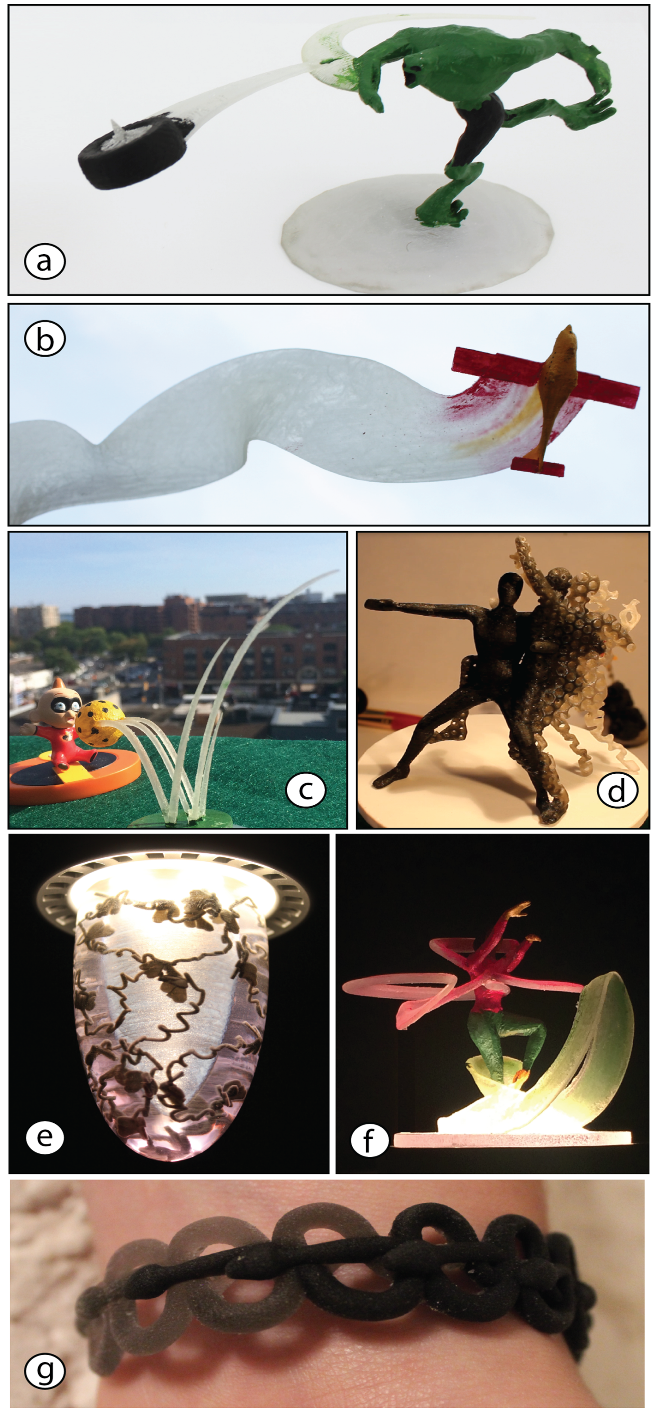

Figure 14: 3D printed motion sculptures modeled with ChronoFab. *Sweep* technique applied to visualize a creature throwing a tire (a), a flying plane (b), and the trails of a dance (f). *Tapered motion lines* depict the motion of a bouncing ball (c). *Multiple stroboscopic stamps* technique depicts an action figure fighting (d) and the movement of a snake as a hand bracelet (g). The combination of *Motion lines* and *Multiple Stroboscopic Stamps* portray flying moths around a light (e).

geometries (*Tapered motion lines*) function as support structures for the original object. We used a *Plane sweep* technique for depicting the trail of a flying plane (Figure 14b) and a dancing ballerina (Figure 14f). *Multiple stroboscopic stamps* technique was used to model the fighting action figure (Figure 14d). The abstraction patterns in the stamps were modeled in Meshmixer [3]. 3D animated objects can also be used for product design. The lamp shade in Figure 14e is designed from the flight of an animated moth, using the combination of *Cylinder motion lines* and *Multiple Stroboscopic Stamps*. The moth, its trail and the shell were printed by a multi-material Objet printer using opaque and transparent photopolymers. The jewelry example (hand bracelet) in Figure 14g is designed using the *Multiple Stroboscopic Stamps* technique of a snake moving along the arm. All these examples illustrate the diversified usages of motion sculptures across application domains.

USER STUDY SESSIONS

We conducted a user study to gain insights on how ChronoFab compares to existing 3D modeling tools and workflows for crafting motion sculptures. We invited both professional and amateur users for a comparative user study, and to gain insights about the usability, limitations and creative usage of our system.

Participants

Six participants took part in the user study, aged 25 to 44 years old (average 34). Among them, three participants (*P4*, *P5*, *P6*) were expert 3D animators and modelers, having at least 12 years of industry experience. We also invited three amateur users who all had some level of familiarity and experience with 3D modeling and/or sculpting tools, but not as a professional.

Procedure

Our user study sessions for each participant lasted between 50-60 minutes. All the sessions took place in our research lab, consisting of the following two steps.

Overview and Training (20 minutes): In this step, each participant was given a brief overview of the system and was shown some resulting 3D printed motion sculptures made with our system (Figure 14). The instructor walked the participant through seven training tasks. The tasks were designed to familiarize the participant with how to generate and interactively control the motion depiction techniques.

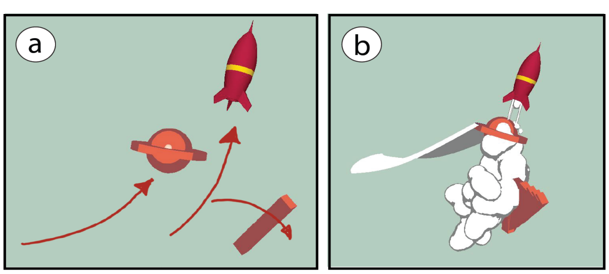

Figure 15: Exercise task (a) Input animation (red lines indicating the motion direction) (b) Target artifact

Exercise Task (30~40 minutes): In this step, participants were asked to reproduce a target motion sculpture (Figure 15) in two separate conditions (*ChronoFab, Traditional)*. In the *ChronoFab* condition, the system, as described above, was used. In the *Traditional* condition, participants were allowed to use whichever 3D modeling tool they felt most comfortable with (i.e., Maya, Meshmixer, ZBrush). The target artifact consists of three *motion lines*, a *motion sweep*, a *multiple stroboscopic stamps* effect and a *particle system* effect. Participants were provided with the necessary input files – a Maya animated scene file and all the 3D static models of the individual objects. The condition orders were fully counterbalanced between participants.

Results

All the participants were able to finish the exercise task in both conditions. On average, the task took 4:25 minutes (*SD* 0.6) for *ChronoFab* and 21:10 minutes (*SD* 2.33) for *Traditional* (Figure 17). This effect of condition on completion time was significant ($t_5 = 16.29$, $p<.001$).

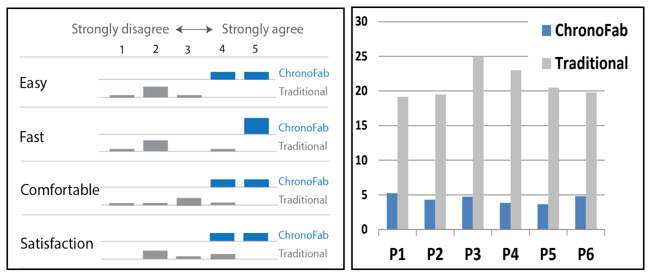

Figure 16: Subjective results from post-study questionnaire (left). Task completion times for each participant (right).

Using *ChronoFab*, participants encountered 2 errors in total, but in both cases recovered independently. *P2* attached a particle system to the flying UFO, instead of the rocket, and later generated the *particle system* from the rocket trajectory. *P5* used *fluids* for the smoke, and later reverted back to a *particle system* for the desired geometry.

For the *Traditional* condition, four participants (*P1, P2, P5, P6*) used Maya and two participants (*P3, P4*) used Meshmixer. Although the animation file was made available for their use, participants mostly used manual sculpting tools (e.g., extrude polygon faces and edges, adding geometric primitives) to generate the geometries.

While our participants (*P1*, *P2*, *P5, P6*) had prior experience with Maya, they were often not aware of tools or workflows that could be used to generate geometries using motion data. For example, to create the smoke trail using Maya, two participants (*P1*, *P6*) repeatedly inserted a number of polygon spheres into the scene. All the participants used sculpting tools to generate the motion lines. This manual use of sculpting tools accounted for longer completion time and lack of precision in the results. Across all participants, there were five instances when participants did utilize the animation – *particle system* (*P2*, *P5*), *animation sweep* (*P2*, *P6*), and *multiple stroboscopic* *stamps* (*P2*). Several participants (*P5*, *P6*) resorted to online help during the task.

In the post-study questionnaire, participants compared the two conditions used to complete the exercise task, based on a set of 1-5 Likert Scale questions (where higher is better). As can be seen in (left), for the given task, participants found ChronoFab to be faster, easier, more comfortable and were more satisfied with the resulting artifacts with ChronoFab compared to traditional tools.

Extended Usage

In addition to the user study, we invited four additional skilled 3D modelers (*P7-P10*) to work with our system to craft motion artifacts of their own. During these usage observations a facilitator assisted the participant when requested. The users authored a range of motion artifacts.

Figure 18a depicts a zoetrope crafted by *P7*, which produces the illusion of motion by using a sequence of 3D models in slightly different poses. The user modeled six different motion sculptures, each of them at a slightly different time interval of an animation. Each of the stamps has *motion lines* added to it. The design took 19 minutes. *P8* modeled a stylized depiction of gaseous emission from a cartoon-like character (Figure 18b). The user started with an existing 3D character and applied the particle system effect to an animated sphere behind the character. The process took 11 minutes. *P9* modeled a procedural geometric shape by first animating a circular disk. He then added *Tapered motion lines* from the vertices in the disc boundary. This artifact took 3 minutes, including the creation and animation of the disc. *P10* crafted an animated rocket artifact with *Tapered motion lines* depicting its trajectory (Figure 18d).

DISCUSSION

In general, the participants responded positively to the simplicity and capabilities of ChronoFab. Participants stated they found our system easy, playful, novel and useful. In the post session questionnaire, the users rated the ease of use as 4.5 out of 5 (*Min.* 4).

Feedback

Participants expressed their high satisfaction to the range of motion effects the system is capable of. Even though our participants never modeled motion sculptures, they expressed their interest in having the tool for a variety of applications, including miniature toy figurines (*P1*, *P2*, *P3*, *P5, P6*), jewelry design (*P7*), communicating information (i.e. speed, trajectory, motion in 3D space) in industrial mock-up models (*P5*), procedural geometric modeling (*P8*), public art installations (*P5*), and architectural design (*P2*).

P8: "*If I had the system I would try printing custom jewelry to create intricate and organic looking bracelets or necklaces. Imagine a smoke trail bracelet or necklace generated from a simple animation of a ball going in a circle.*"

Users also pointed out a few limitations that could guide future enhancements. Several participants (*P3*, *P4, P5, P7*) recommended having more sculpting tools in our user interface for greater artistic control and finer details. Users also suggested taking acceleration and velocity into consideration (*P2*, *P8*) when generating motion geometries.

Expressiveness vs. Ease-of-usage

ChronoFab is a special-purpose 3D modeling tool tailored for motion sculptures. As such, it is not directly comparable to general-purpose 3D modeling and animation tools which often have hundreds of controllable parameters Participants (*P3*, *P5*, *P6, P8*) commented that the ChronoFab system facilitated rapid exploration by significantly speeding up the process of geometry generation from 3D animated objects and automating the steps. However, it is worth noting that, artists as a user group do not always seek to achieve a task quicker. ChronoFab is more suitable for early stages of design for rapid exploration [28] and form finding. Experienced artists can always use existing sculpting and modeling tools for intricate details and personalization.

P3: "*Although I'll have a lot of control over the shape by sculpting, it will take a lot of time and will be difficult to follow an animation if that's desired. It would be easier just to use your system to make the feature, then add details via sculpting.*"

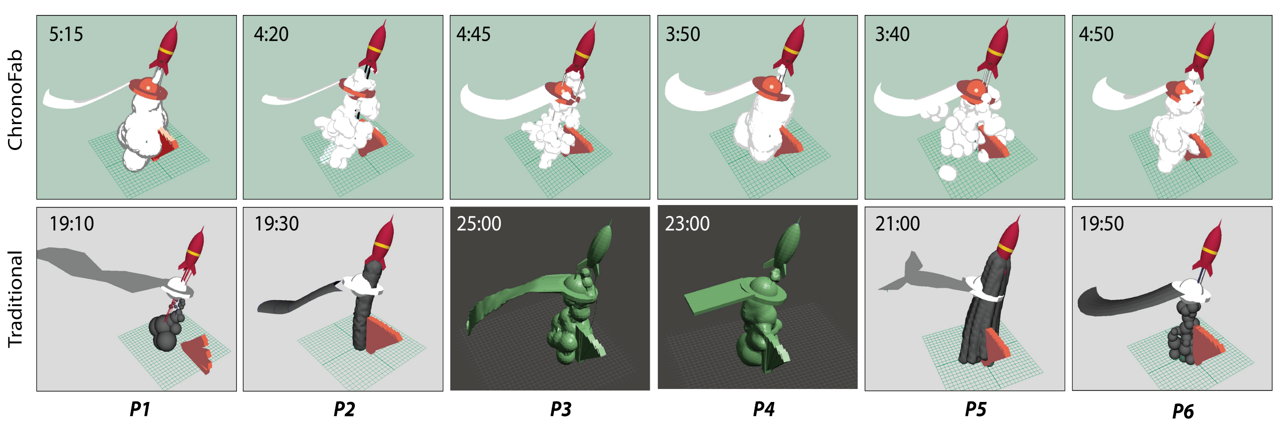

Figure 17: Resulting artifacts in the exercise task using ChoronoFab (top row) and existing tools (using Maya and Meshmixer) by the participants. The number in each panel indicates the time required to complete the task.

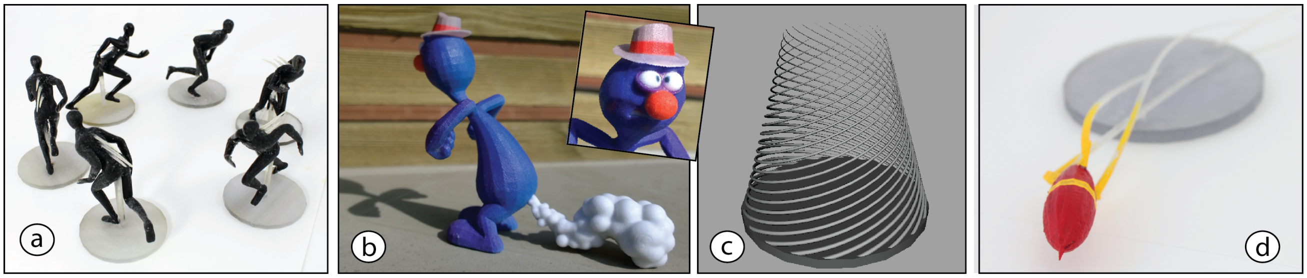

Figure 18: Artifacts modeled by external users (a) Zoetrope (b) Gas emission (c) Procedural geometry (d) Rocket

GENERALIZABILITY AND IMPLICATIONS

ChronoFab offers a fundamentally new interactive workflow: Aiding and enhancing 3D modeling techniques by incorporating time, motion, and animation-driven simulations. As we have shown in our work, this is a powerful concept that allows for the efficient and flexible creation of motion sculptures. However, this core concept may extend further with broader implications.

Dynamic sculpting for 3D modeling

One way in which our work may be generalized is the development of 3D sculpting tools that have any awareness of back-end animation data of how a model moves or deforms over time. This would contrast traditional modelling tools which consider only the local geometry and tool parameters. For example, consider having dynamic simulations in a sculpting tool that serve as smart templates or guides for editing manipulation. Or perhaps subtle visualization could reveal local animations that occur at specified areas of a model. We believe there could be a whole class of such "animation-aware" modeling tools and systems, beyond the techniques introduced in our paper.

Novel Approaches to Design Problems and Ideation

Dynamic sculpting can also offer a novel approach to design problems and ideation. While form as a product of dynamic simulation has been explored previously [1], ChronoFab demonstrates the use of motion data as a way of crafting compelling, sophisticated forms quickly and easily. There is a growing corpus of available animation data from motion capture systems, simulation methods, procedural methods, and manually crafted character animations. The integration of such motion data into modeling environments opens up the possibilities for a more dynamic framework in the early stages of design. Static visualizations of motion data, dynamic simulations, and forces over time, can serve as inspiration during the form finding process. For example, as demonstrated in this paper, a flying moth animation may inspire a lamp design (Figure 14e), or a character animation can inspire a jewelry design (Figure 14g).

Generative Design

Another promising avenue for utilizing temporal information in the modeling process is for generative design. In generative design, sophisticated and complex geometries can be represented with small amount of data (e.g., rules, codes, parameters). While the interface components of ChronoFab are inspired from existing motion sculptures, generative designers can write customized rules and codes to generate complex, organic, or repetitive forms using motion data. Together, a number of these tools can be integrated as part of the larger generative design process for new sophisticated designs.

Physical Visualization

By developing tools for crafting physical visualization of motion, our work bridges the gap between 3D animation and physical visualization. Motion is a form of time-varying data. Indexing time in physical artifacts is not just a visual phenomenon, rather it offers new forms of expression for the physical visualization of data [31] that changes over time.

FUTURE WORK

In the future, we intend to explore interfaces that engage motion and time in other forms of 3D modeling. It would also be interesting to investigate the use of static 3D models or video as input for motion sculptures. Currently, our tool only visualizes structurally weak regions of the 3D model. A semi-automatic approach to make the models structurally stable and strong [21] by skewing (e.g., deformation, parameter tweaking) the motion geometries presents an interesting optimization problem. This remains as future work. While previous works analyze the strength of an object as a single material object, balancing the structural integrity of multi-material 3D printed objects also remains an interesting and challenging technical problem.

CONCLUSION

Greg Lynn's seminal book "Animate form" [13] advocates the use of time-based animation techniques for architectural designs that inspired an entire generation of architects to a new way of thinking. Despite the experiments by visionary artists and architects, the use of motion and forces (simulation) as a way of designing static 3D forms is relatively less explored, in particular from an HCI perspective. Guided by our observations, we have designed and developed ChronoFab, a system enabling both amateurs and experts to rapidly explore and craft *motion sculptures* from 3D animated objects using time and dynamic simulation. The user study and resulting artifacts indicate the ease of usage, expressiveness, and creative possibilities of dynamic sculpting for variety of 3D modeling tasks.

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