Report Number: WUCSE-2011-57

2011

Results of an observational study on sketching

Cindy Grimm

We present the results of an observational study on sketching. Artists were asked to sketch a small number of objects and comment on how and why they made the marks they did. We summarize these findings, from low-level details on individual marks through the drawing construction order. Based on these observations we provide suggestions for future research directions in 3D sketching.

2011-57

Results of an observational study on sketching

Authors: Cindy Grimm

Corresponding Author: cmg@wustl.edu

Web Page: http://www1.cse.wustl.edu/~cmg/drawing.htm

Abstract: We present the results of an observational study on sketching. Artists were asked to sketch a small number of objects and comment on how and why they made the marks they did. We summarize these findings, from low-level details on individual marks through the drawing construction order. Based on these observations we provide suggestions for future research directions in 3D sketching.

Type of Report: Other

Washington University in St. Louis (2011), pp. 1–7
Technical report

Results of an observational study on sketching

Cindy Grimm

Abstract

We present the results of an observational study on sketching. Artists were asked to sketch a small number of objects and comment on how and why they made the marks they did. We summarize these findings, from low-level details on individual marks through the drawing construction order. Based on these observations we provide suggestions for future research directions in 3D sketching.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Line and curve generation

1. Introduction

This paper presents the results of an observational study on how artists draw, conducted in the summer of 2010. The goal of the study was to gain insight not just into how marks are made on the paper, but the entire process of creating a drawing — how and why artists chose the lines they do. Although each participant had their own style, there was commonality in both how they made marks on the paper and the order in which they built up the drawing. Common across all participants was that the 2D aesthetics of the drawing — weight of light and dark, placement of lines on the paper — was just as important as capturing the lines of the shape.

The participants worked primarily in pencil, pen, and charcoal, with a few examples of ink or brushes. Since the artists knew the eventual goal was to develop a 3D sketching system they tended towards linear drawings, although they were free to, and even encouraged, to add contouring strokes or shading.

The study is summarized in Section 2. In Section 3 we summarize our observations on use of media, types of strokes, and on drawing construction. In Section 4 we outline possible improvements to existing sketching and painting systems. Some of these directions are based on suggestions from the participants — what they would like to be able to do. Others are based on existing artistic actions in traditional media that could be exploited to make the digital experience more natural or easier to control.

Books on how to draw can be a great source of knowledge about how artists draw, but they also present a somewhat simplified view of the drawing process. They also tend to consist of guidelines, which are routinely broken by artists in practice. This study is meant to complement book knowledge by providing concrete examples of how different individual artists approach the same, relatively simple, subjects.

Contributions: The primary purpose of this paper is to encourage researchers to think more holistically about the sketching process, from making marks on the paper through exploiting semantic and structural awareness as the sketched shape evolves. We provide classification and description of these components in the text, and concrete examples in the accompanying video. We also outline several possible research directions, both short-term and long-term. Finally, we hope to convince people of the utility of using observational studies to gain a deeper understanding of the sketching process.

2. Study outline

The author selected a small number of relatively simple shapes that had the following properties: 1) The ranged from man-made (the train) to more organic shapes (the horse). 2) Several objects had elements that could not be captured with planar curves (eg, the horse's leg and Mr. Potato Head ®'s arms). 3) The objects were simple enough that they could conceivably be created with a 3D sketching program.

The participants were asked to chose one or more of the models, and to draw them from whatever view and in whatever media they wished. For view angle, they were asked to chose a view they thought was informative or interesting. The drawing surface was video taped as best as possible without interfering with the drawing process. Participants were asked to talk about what they were doing and why if they felt comfortable doing so (about half did so).

Figure 1: *Variation in marks made by a single tool.*

After each drawing they were asked leading questions such as "Why did you put that line there?" in order to elicit further information if necessary.

There were 11 participants. One was an art student, the remainder were recruited from two local artist's associations. These participants had little, or no, computer experience and had been working with traditional media from five to eighty years, and included several professional or semi-professional artists. Study sessions averaged around an hour, with 20-40 minutes of recorded drawing. The non-drawing time was spent explaining the purpose of the study, determining a good filming location, and discussing the drawing processes.

Photographs of all of the drawings (except participant 10) are included in the supplemental materials.

2.1. Previous work

Perhaps the closest study to ours is the one on silhouettes by Cole et al [CSD*09]. In that study artists were asked to draw lines that best depicted the object. The artists were working from photographs (and asked to copy their lines as best as possible back to the photographs) so that the drawings could be analyzed for commonality of lines. We were less concerned about capturing the specific lines drawn and more about the drawing *process*, in particular how artists mapped 3D shapes to marks in the drawing plane. Working from 3D shapes is also very different than working from a photograph, which is essentially a 2D to 2D mapping. We therefore have more qualitative data and less quantitative. That said, even in our more free-form study we saw the same similarity and general placement of silhouette and interior contour lines as in their study, indicating that their results may hold even in this more general setting.

Similar to Schmidt et al's study on drawing in perspective [SKKS09] we also saw that even trained artists have difficulty getting perspective correct. Interestingly, most of them were not that concerned about getting the perspective "correct" (as long as it was not too noticeably distorted), but cared more that the 2D lines were aesthetically pleasing and captured the "interesting" features and lines of the model. Many of them actually deliberately introduced distortion (with comments such as, "I know this isn't really that big, but it looks better that way".

3. Study observations

We break our study observations into five categories, working from low-level to high: Expressivity of the media, control of the media using external objects, making strokes, types of strokes, and drawing construction. These observations are based in part by examining the videos, and in part on conversations with the artists about why they placed particular strokes where and how they did.

3.1. Expressivity of the media

Even with pencil and pen there was a surprising amount of variation in the marks made by a single tool (see Figure 1). This expressivity was enhanced by using a shaped tool (a rectangle cut at an angle to the drawing surface). We break down this variation by what they were physically changing, and the resulting variation in the stroke.

- *Variation of pressure:* For pencil and charcoal, pressing harder results in a darker line. Even with pencil and pen, pressing harder also resulted in a fatter line. This is more pronounced for charcoal.
- *Variation of angle by rotating the tool:* For non-circular tools (eg angled markers and pens) rotating the tool changed the thickness.

- *Variation of speed:* Moving faster usually results in a lighter line, particularly for pen and charcoal.
- *Variation of angle by tilting perpendicular to the drawing direction:* For angled tools, such as pens, fat pencils, and shaped charcoal, this results in a fatter line as more of the media comes in contact with the surface. For circular tools, laying it nearly perpendicular to the surface results in a fat, usually lighter, stroke. By combining angle with rotation a shaped pencil can go from a very thin line to a wide, shading stroke.
- *Variation of water amount OR using a smudging tool:* Adding water or smudging lightens the tone and (usually) broadens the stroke. Adding more water or using a wider, already coated smudging tool creates more diffusion or spread.

This variation has been documented in the past and (particularly for pressure) is commonly used in tablet-based drawing and painting systems.

3.2. Control of the media using external objects

For pencils and charcoal there are smudge sticks and erasers. For ink there are sponges, stones, and water. Erasers and smudging implements were sometimes wielded by the non-dominant hand. Both erasing and smudging can be used to lighten and broaden lines, softening the boundary between media and paper. For ink or single-color brush painting, the stone or palette is used to control how much ink is on the nib or brush, and how watery the ink is. Sponges can be used on the paper itself to wick away water and smudge, or externally to remove water from the nib or brush before stroking. Typically the artist makes several strokes, then re-loads the nib or brush, optionally adjusting the water-ink balance.

Many systems support smudge sticks and erasers as tools. However, using interactions with non drawing-surface objects to control inking in painting parameters is less well-expored. We discuss several possible possibilities in Section 4.

3.3. Making strokes

We define a "stroke" as being a line with semantic meaning, such as the silhouette of a body, the outline of an eye, or an interior contour or shading line. A "mark" is defined by the tool touching the paper, moving, then lifting up again. In many sketching systems the two are considered to be the same thing [NISA07, CA09], although some systems support merging several overlapping marks into a single stroke [BBS08]. From our observations, it usually is not that simple — we show examples in the accompanying video.

Marks, in our study, ranged from short, centimeter long motions to entire contours. Shorter, straighter marks tend to have a fairly uniform speed. More complex marks often had pauses, usually at inflection points, where the artist rotated the tool or changed the angle before continuing the mark. Marks often re-traced themselves, an action we call "scratching over". Some artists moved the tool in an arc, scratched back over the end, then continued the mark, and so on, often several times.

The relationship between marks and strokes can be complex. Most of the time, one or more marks make up a stroke. Usually these are continuous in time and space, ie, the artist creates the stroke by laying one or more marks down with subsequent marks either continuing an existing mark or darkening or changing slightly a previous mark. Usually the artist lays down marks in a single direction, but occasionally they will work from the inside out, extending an existing stroke from both ends. Sometimes the initial marks were not continuous, but were joined by later marks into a single stroke. Quite often the artist will outline an initial stroke with several marks, then return to it later to add more, usually darker and wider, marks.

A single mark may belong to more than one stroke. This happens, for example, when the artist is tracing a silhouette of the object. They may, in one mark, follow the outline of the hat to the body to the foot (Mr. Potato Head®) or, in the case of the horse, follow the contour of the back down through a leg. Sometimes the change from one stroke to another is obvious (there is a change of direction or speed), but not always — especially if the silhouette or contour they are drawing is visually continuous, at least in 2D.

In our study we only saw a few instances of erasing, probably because the majority of our participants used ink, and these were not "final" drawings. However, initial marks for a stroke were sometimes over written or replaced with new ones, usually darker. Occasionally marks were obliterated using shadow or contour marks. Generally, marks got darker and broader as the artist finalized the stroke. One thing to note here is that preliminary marks may help guide the artist toward the final stroke shape, but they should not be *blended* together. For charcoal, pencil, and ink preliminary marks that did not coincide with the final stroke were often either smudged out into shading marks or obliterated altogether using shadow marks.

Although painting and image-based systems do not require the identification of strokes per-se, there are many cases where collecting marks into strokes is useful. For example, semantic editing, where a group of marks that represent a single object are edited as a unit. Another example is building 3D models from sketching. Existing applications that need strokes currently take one of the following approaches:

- Require each stroke to be made with a single mark.
- Support limited marks to strokes, either allowing multiple, overlapping marks or allowing an existing stroke to be over-sketched with a new mark, replacing the overlapping part of the curve.

- Digitize the marks into an image then run an edge extraction algorithm on the resulting image.

We argue in Section 4 that a system for intelligently collecting marks into strokes would be very useful, and suggest possible directions based on specific use-cases.

3.4. Stroke types

The majority of strokes in our study were, of course, used to outline the shape (interior and exterior silhouettes, suggestive contours) but there are other types of strokes as well.

- *Placement and alignment strokes:* These are short, usually straight lines that the artist uses to block out the eventual locations and alignment of objects (such as the top and bottom of the body). Nearly all of our artists sketched these lines, but many of them sketched the lines in the air over the paper rather than making marks on the paper. These strokes tended to occur before the artist began working on a new component.
- *Shadow strokes:* These are strokes placed either at the ground contact points of the object or behind the object and serve to anchor the object so it doesn't look like it's floating. Shadow strokes were also used to cover up old silhouette marks. The directionality of the shadow strokes was either used to convey a light source direction (typically with ground plane shadows) or based on the silhouette edge direction (typically perpendicular or near perpendicular).
- *Over marking strokes:* These are darker strokes placed over existing ones, usually added after most of the shape was sketched. These are used to strengthen, or emphasize, a contour, and provide perceptual depth contrast between shapes.
- *Contour strokes:* These are strokes placed in the interior of the object to indicate its internal shape. These strokes largely correspond to highlights on the object. Some artists placed contour marks parallel to edges, some perpendicular, and some made a zig-zag or other shape (see Figure 2). Interestingly, the contour strokes appeared in roughly the same places, even though the lighting conditions varied widely from single-source illumination (sunlight through a window) to multi-source (overhead fluorescents). Several artists actually made comments to the effect that "...the lighting in here is bad, but there should be a contour here...", indicating that these strokes are a form of short-hand for indicating what the curvature would be under some sort of "default" lighting.
- *Detail strokes:* These are strokes which correspond to color or small-scale surface variation of the objects (the pattern on the lamp, Mr. Potato Head®'s shoelaces).
- *Shading strokes:* These are a variation on contour strokes, made using the broad side of the pencil or charcoal or with a brush. They lack the directionality of contour strokes and tend to form shapes rather than lines. Although they are used, like contour lines, to give 3D shape, they also serve a role in balancing the light and dark patterns on the paper. I.e., their shape and intensity were as much dictated by 2D aesthetic decisions as they were by efforts to capture the 3D shape.

3.5. Drawing construction

We analyzed the videos to determine if there were any commonalities in how the artists approached constructing their drawings. Broadly speaking, the artists tended towards the following stages. These stages held both at the entire drawing level (getting started) and at individual components where relevant (body or sub parts).

1. Rough blocking of where the object would appear on the 2D surface. There were not usually marks, per-se, associated with this stage. Instead, the artists would mark of areas with their hands (framing) on the paper, followed by sketching in the air. The latter happened quite frequently, as if the artists were practicing and visualizing the marks before committing to making marks.
2. Outline or outer silhouette curve followed by the majority of the interior detail. Interior detail includes both contouring and detail strokes.
3. When placing the outlines and detail the artists tended to start and one point and "sweep" across the model. These sweeps were predominantly top to bottom or from side-to-side (which direction was dictated by the overall orientation of the object).
4. A return to detailing items that may have been missed or only outlined in the initial sweep.
5. Adding interior shading, followed by ground plane and background shadow strokes.

There appears to be two competing trends. The first is to do structural lines first (exterior and interior silhouettes) followed by interior detail (contour lines and detail). The second is to add lines close to existing ones, usually sweeping in one direction, but sometimes spiraling around. This implies that spatial coherence and proximity is just as important (or more so) than the more abstract concept of stroke type. Jumping around happened only at the end, when the artist was making small adjustments to the contours and adding shading.

We provide specifics for four cases where we had several artists sketch the same shape (Mr. Potato Head®, the teapot, train, and the horse).

3.5.1. Mr. Potato Head®

Participant 1 (marker): Front view: Marked out body shape on paper, drew hat then body with eyes. Moved from left to right: arm, glasses, right arm. Then moved top to bottom, nose, mouth, shoes. Included detail on shoes. Returned to detail on eyes, hat, arm. Side view: Started with body, then worked down from the top: hat, eyes, nose. Continued with

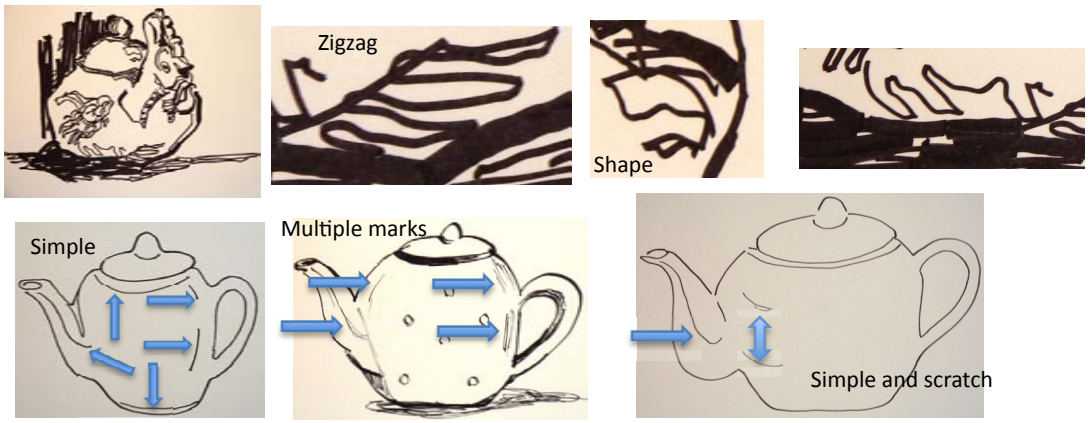

Figure 2: *Different contour marks.*

Table 1: *Stats on drawing order for Mr. PotatoHead®, teapot, train, and horse.*

Action	PH	TPot	Train	Horse
Turned paper	1	1	0	0
Top to bottom	13	2	8	0
Bottom to top	0	0	4	0
Left to right	3	1	5	2
Right to left	2	1	3	2
Around	4	3	1	3
Detailed immediately	10	2	6	1
Detailed afterward	9	3	7	2

arm, then moved down to feet, adding detail. Returned to top, adding occluded arm, glasses. Added detail to hat.

Participant 2 (fat marker): Started with hat, then nose. Sketched right side of body and did feet (right, left, no detail). Moved up to left side arm, then across to add eyes and glasses. Added contouring lines to body and hat. Added detail to feet, then body and hat. Then added detail, contour, and shadow marks to the entire drawing.

Participant 4 (marker): Started with glasses, then hat, then body flowing into right arm. Added nose then left arm. Moved down to add feet with detail.

Participant 5 (sumi ink): Hat with some detail than body outline. Moved to right arm then eyes with glasses and the nose. Down to feet then back up to left arm. Then added wash to body and nose to provide shape information.

Participant 5 (charcoal): Hat with some detail than body outline. Added outline for eyes and nose. Added detail to eyes. Added glasses. Added shading to body and hat then moved to right arm. Shaded right arm them moved to left. Added feet with detail.

Participant 8 (pencil): Started with body shape then added feet with detail. Added left arm followed by right arm, then eye outline. Added hat then returned to eyes and added detail and glasses. Moved down to nose. Added additional detail to shoes, glasses, body, hat.

Participant 9 (pencil): Started with hat then body shape then feet with detail. Added eyes with glasses. Did left arm followed by right one.

Participant 10 (charcoal): Outlined body and feet shape, then hat. Worked down adding eyes, glasses, and nose. Added left arm and detail to feet.

Participant 11 (pen): Outlined body and hat shape, then worked around, right arm, feet, then back up to eyes and glasses, then down to nose and mouth. Returned to detail glasses and shade body. Added left arm. Added shading marks to right arm, feet, left arm, hat, body, feet. Finished with ground-plane shadows.

3.5.2. Teapot

Participant 2 (fat marker): Top, left half of body, spout, right half of body. Returned to spout. Added more ground plane and shadow marks. Interior contour and detail marks. (Note: This was a slightly different teapot with more detail on the spout).

Participant 4 (marker): Entire silhouette, lid, then interior contours (first version). Lid, silhouette, interior contours (second version).

Participant 7 (pencil): Sketched outline, then worked right to left (spout, top, handle). Added detail.

Participant 11 (pen): Silhouette, left to right (spout to handle). Lid with shading. Interior shading then ground plane shading. Detail.

3.5.3. Train

Participant 3 (pencil): Middle, up to smoke stack. Right to front of train; top to bottom, included detail. Added more detail to middle. Top of wheels then back of train, working from top to bottom. Left to right on the wheels. Added more detail to the front, then the back. Erased and fixed back.

Participant 4 (marker): Front, inside out, then bottom. Smoke stack, bottom to top. Top, from left to right, then down to body. Wheels, right to left. Shading wheels, body, front, smoke stack, bottom.

Participant 5 (charcoal): Top middle of train, right to smoke stack and front. Top to bottom of front, then right to left for wheels. Shaded top to bottom back, then left to right top. Right to left on wheels, then ground plane.

Participant 6 (pencil): Front, top to bottom. Front wheels, then back wheels, both bottom to top. Added wheel connector, detail to top and back.

Participant 11 (pen): Front, top to bottom. Wheels, left to right. Two body lines, then detail on the front. Added top, moving left to right. Shaded wheels and ground plane, then shaded top to bottom (front). Added detail to body.

3.5.4. Horse

Participant 4 (marker): Around exterior silhouette. Head, back leg. Detail on neck, head. Background shading to adjust silhouette. Interior shading, left to right.

Participant 5 (sumi ink): Back to back leg, second back leg. Neck and front leg. Return to back. Stomach. Return to neck, added head, other front leg. Shaded left to right.

Participant 9 (pencil): Exterior silhouette (body) and interior contours (body). Neck and head. Front leg. Tail. Shading.

4. Discussion and suggestions

We provide suggestions in three categories. The first is a look at interactions that artists do naturally already, and how they might be exploited to control attributes of a digital environment. The second is how to make a stroke-based system more natural and sketch-like. The third is editing tools that would leverage the semantic content of the drawing to make meaningful, large-scale changes to drawings.

4.1. Off-screen indirect tools

While many painting and stroking applications take advantages of angle and pressure information for controlling media as it is applied to the surface, we are not aware of any that use these pen attributes to control how media is applied to the brush (eg, how watery, how mixed, how dark, how thick). Artists use a variety of objects (ink stones, water jars, palettes, paper towels) to control this. Physically moving the brush "off-screen", as it were, between when needed to reload the brush with ink or change the water content (and hence the diffusion properties) is very natural. The following are some straight forward suggestions for incorporating these "off-screen" stand-ins.

1. Sumi inkstone well: Dragging the brush further up the stone dries it out.
2. More pressure on the ink picks more up. The angle and orientation affects what part of the brush is loaded with ink (enabling one-sided ink loading).
3. "Mixing" the ink with water by swirling the pen in the ink well increases the uniformity of the ink to water ratio.
4. Pushing down on a paper towel reduces the water content.
5. "Dragging" the pen over a "water-jar lip" squeezes water out of the brush based on the pressure and angle of the pen.
6. "Swirling" the pen in the water jar removes ink.
7. A virtual "knife" for changing the cut angle on a pencil or pen. The angle of the pen as it is pushed onto the knife indicates the cut angle.

4.2. Marks into strokes

One largely untouched area in sketching interfaces is how marks are accumulated into strokes. Most sketching and diagraming applications enforce a "One mark, one stroke" rule, or possibly a sequence of overlapping (in both time and space) marks makes a stroke [SKSK09]. Overstroking is also available in some systems, although usually as a specific select the curve and apply an overstroke "brush" operation. From our analysis of actual drawing styles, a more natural system would also enable (see Strokes video):

- Strokes made from discontinuous marks that are both visually continuous and belong to the same contour (usually caused by occlusions — see the teapot lid and handle in Figure 2).
- Strokes made from multiple marks that overlap at the ends. A flexible approach would allow for adding at either end and in either direction, and allowing breaks between marks that are later filled in with additional marks.
- Allowing marks that overlap themselves, in a scratch back and forth motion. This includes individual marks made by moving the pencil or pen back and forth over the same line multiple times, and also a forward, back part way, forward again motion. The latter is similar to the multiple mark stroking above, except the artist never lifts the pen or pencil up.
- Being able to return to existing strokes and add more marks to them or overstroke without requiring a specific selection step.
- Breaking of long marks into semantic segments (eg, the teapot spot from the body).

Obviously, different artists have different drawing styles, and their drawing style may be different based on what media they are using. Ideally, the system would learn what their

drawing style is and adapt to that (ie, they favor long strokes or they like to scratch back and forth).

4.3. Re-shaping drawings

One obvious advantage of computer-aided drawing is that it is possible to pick up and move around strokes. Nearly every drawing system has the ability to rotate, scale, translate, or keystone strokes or groups of strokes. Many systems also support rectification of some kind — right angles, straight and parallel lines, circles, etc. Few systems, however, allow the artist to semantically group marks as 2D strokes representing the boundaries of 3D objects. The ability to quickly build approximate 3D geometry and embed the 2D strokes on that geometry would support the following:

- 3D beatification and rectification of lines that, together, represent circular and rectilinear 3D objects. Includes symmetry correction for 3D objects from arbitrary views.
- Include rotation in and out of the image plane.
- Perspective rectification (ie, convergence for parallel lines, correct rendering of cylindrical objects).
- Small-scale viewpoint adjustment.
- Various local non-linear perspective effects such as fish-eyes and panoramas.
- Semantic editing of parts, ala IWires [GSMCO09, ZFCO*11].

Schmidt et al [SKSK09] showed that 3D "scaffolding" can be very useful in constructing and disambiguating 3D drawings. In some sense what is needed is a light-weight way to build temporary scaffolding on existing drawings semi-automatically; this scaffolding could then be used to perform editing or rectification. There is a large body of existing work on building 3D shapes from line drawings; what is needed here, though, is something slightly different:

- Fitting approximate proxy geometry to the sketch — ie, the entire, exact 3D shape does not need to be reconstructed. Rather, the 3D geometry plays more the role of a free-form deformation controller.
- Identification of detail and contouring strokes. Not all strokes contribute to the 3D geometry. Ie, the system needs to be able to recognize, and ignore, strokes that are not structural (eg, shading, contour, detail, placement marks).
- Approximate depth assignment sufficient to perform perspective changes [TDM01].
- There is a user in the loop who can add additional strokes or input and help to disambiguate cases [IH06].

5. Conclusion

Computer-aided sketching and painting has come a long way, but there still is plenty to be learned from the traditional drawing process. While simulating artistic media has received a great deal of attention, understanding, and enhancing, how artists interact *with* the media has seen less attention. Similarly, there has been a focus on how to manipulate individual curves and stroke, but not on understanding and exploiting the semantics and stages of the drawing process. This paper, and the accompanying videos, hopefully provide sufficient background, information, and motivation for addressing these challenges.

6. Acknowledgements

I am deeply indebted to the artists for inviting me into their studios and for taking the time to create drawings and talk about their drawing process with me. Our conversations were both interesting and enlightening, and the drawing process fascinating to watch.

Note: The actual quality of the videos and images is higher than those submitted (substantial compression was necessary to fit in the 30MB limit). Audio has been removed from the video. PotatoHead, Train, and Strokes are all at 2X speed.

References

[BBS08] BAE S.-H., BALAKRISHNAN R., SINGH K.: Ilovesketch: as-natural-as-possible sketching system for creating 3d curve models. In *UIST '08* (New York, NY, USA, 2008), ACM, pp. 151–160.

[CA09] COOK M. T., AGAH A.: A survey of sketch-based 3-d modeling techniques. *Interact. Comput. 21* (July 2009), 201–211.

[CSD*09] COLE F., SANIK K., DECARLO D., FINKELSTEIN A., FUNKHOUSER T., RUSINKIEWICZ S., SINGH M.: How well do line drawings depict shape? In *ACM SIGGRAPH 2009 papers* (New York, NY, USA, 2009), SIGGRAPH '09, ACM, pp. 28:1–28:9.

[GSMCO09] GAL R., SORKINE O., MITRA N. J., COHEN-OR D.: iwires: an analyze-and-edit approach to shape manipulation. In *ACM SIGGRAPH 2009 papers* (New York, NY, USA, 2009), SIGGRAPH '09, ACM, pp. 33:1–33:10.

[IH06] IGARASHI T., HUGHES J. F.: A suggestive interface for 3d drawing. In *ACM SIGGRAPH 2006 Courses* (New York, NY, USA, 2006), SIGGRAPH '06, ACM.

[NISA07] NEALEN A., IGARASHI T., SORKINE O., ALEXA M.: Fibermesh: designing freeform surfaces with 3d curves. *ACM Trans. Graph. 26* (July 2007).

[SKKS09] SCHMIDT R., KHAN A., KURTENBACH G., SINGH K.: On expert performance in 3D curve-drawing tasks. In *Proceedings of EUROGRAPHICS Symposium on Sketch-Based Interfaces and Modeling (SBIM)* (2009), pp. xx–yy.

[SKSK09] SCHMIDT R., KHAN A., SINGH K., KURTENBACH G.: Analytic drawing of 3d scaffolds. In *ACM SIGGRAPH Asia 2009 papers* (New York, NY, USA, 2009), SIGGRAPH Asia '09, ACM, pp. 149:1–149:10.

[TDM01] TOLBA O., DORSEY J., MCMILLAN L.: A projective drawing system. In *Proceedings of the 2001 symposium on Interactive 3D graphics* (New York, NY, USA, 2001), I3D '01, ACM, pp. 25–34.

[ZFCO*11] ZHENG Y., FU H., COHEN-OR D., AU O. K.-C., TAI C.-L.: Component-wise controllers for structure-preserving shape manipulation. *Computer Graphics Forum (In Proc. of Eurographics 2011) 30*, 2 (2011).