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Design and Evaluation of a Tactile Texture Production System

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Design and Evaluation of a Tactile Texture Production System

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Abstract

Students who are blind or have low-vision (BLV) do not have the same access to graphical curricular content as their sighted peers. This significantly affects their education, particularly in STEM subjects. Introduction of interactive tactile graphics is one of the only ways for BLV students to access graphical content, and is uniquely suited to teaching drawing skills. The goal of this engineering design project was to expand the capacity of printing technology that produces interactive raised-line graphics by creating a system to print textures that meet specific criteria for usefulness. The addition of textures to tactile graphics is essential for the graphics to be unambiguous and to communicate information about spaces and regions. Maps, geometric figures and graphs are prime examples.

The system developed in this project for printing tactile textures was designed as an enhancement of an existing beta prototype printer for interactive tactile graphics co-developed at UVM and E.A.S.Y. LLC. Preliminary experimentation indicated that varying the size of the drawing stylus tip would afford the greatest range of printed textures. Based on this finding, the Texture Creation System (TCS) was designed with this new functionality. This thesis describes the process by which the categories of possible designs were refined and how the TCS - based on a system of interchangeable self-locking tapered tips - was designed, built, revised, and tested.

We developed a set of six tactile textures (the Texture Set) as examples of the capabilities of the TCS. We then designed and performed an experiment in which six BLV subjects assessed the textures based on their Distinctness, Recognizability, and Variability in Degree. In all tests that mimic real-world use, the Texture Set was found to be successful in at least 75% of trials. The design also successfully addressed constraints for speed of operation, system cost, noise volume, and compatibility with the beta printer. The design also met standards for reliability and mechanical strength. Future engineering will be required to add sensors to monitor mechanical operation. Also, larger-scale user testing of the Texture Set (and other textures) will be needed for statistical significance and to provide insight into what objective properties of the textures elicit certain subjective responses, *i.e.* why certain textures meet design criteria better than others.

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I would also like to say thank you to Jan, and everyone at New Moon Cafe for keeping me caffeinated enough to finish this thesis on time.

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Chapter 1
Introduction

1.1 Impact

Individuals who are blind or who live with low vision (BLV) have historically had limited access to graphical content, making it more difficult for them to succeed in school and in the professional world, especially in the fields of science, technology, engineering, and mathematics (STEM). Graphics can range from simple line drawings to complex engineering diagrams and plots, and they all need to become fully accessible to BLV students and professionals. New technologies have been improving this situation, and the project documented in this thesis sought to take another step towards full access to graphical content.

Tactile graphics have been used for some time in classroom settings, but they are usually in a form that does not allow BLV individuals to interact with the graphic. Without interactivity, BLV students are able to "read" and understand a geometry exercise about bisecting angles, for example, but have no means to respond graphically and draw a bisecting line. Being able to interact with graphics is crucial for full and equal access to education for BLV students [16]. This work focuses on expanding the content that can be communicated on the only available interactive tactile graphic medium; in particular, the purpose is to create a system for printing textures on that material, to make the resulting graphics closer to an inclusive translation of graphics for sighted students.

1.2 Background

Often, tactile graphics are made by Teachers of the Visually Impaired (TVIs) using whatever they have on hand. Puffy® paint and hot glue guns can be used to draw lines, and pieces of sandpaper and felt cut and glued to distinguish different areas [11].

These graphics are often effective for communication to the students, but they have two major flaws. First: they are very labor intensive to make, a serious problem when TVIs need multiple copies of a graphic for a class. The second issue is that the quality of these graphics is dependent on the skills, experience and resources of TVIs who make them, reducing the uniformity of curricular content provided to multiple students.

Repeatability of tactile graphics was first possible with the invention of the Thermoform machine in 1962 [3]. This machine uses a 1300 Watt heater and 22 in Hg vacuum to form a thermoplastic sheet on a male master mold [5]. The sheet retains the shape of the master and becomes a permanent tactile graphic copy. This system allows large quantities of graphics to be made relatively quickly, opening the door to standardization of graphics in curriculum for BLV students across the country. Tactile graphics made in this way are very high quality, and the only major downside of the system is that the masters are labor intensive to make, so it is not a practical solution if a TVI only needs to print a few copies of a graphic.

The Tiger embosser series, first on the market in 2000, addresses some of the shortcomings of the Thermoform technology [4]. They create graphics by embossing a series of Braille sized dots onto standard Braille paper, 230gsm weight. These embossers print graphics from digital files at a rate of 1-6 pages per minute [15], and do not require fabrication of a positive master.

Whereas they differ in materials and mechanics, these systems for making tactile graphics share the same limitation; they produce "read-only" graphics. There is no way for a student to interact with these graphics, so their uses are limited. They are useful in cases when the graphic is meant to be explanatory or descriptive, a diagram of a cell in a biology textbook for example, but they cannot be used when the student needs to respond graphically, as may be required for a geometry homework assignment.

The first documented process by which BLV individuals could create an instantaneous tactile graphic by freehand drawing - analogous to pencil on paper – was first described in a 1949 patent by Harry P Sewell [19]. This technique, in the current iteration that is the focus of this thesis, uses tactile drawing sheets (TDS), made from a thermoplastic, primarily PVC and is approximately the thickness of a piece of printer paper. In common use, BLV users draw raised lines manually on TDS by *scratch embossing* over a compliant rubber backing (Durometer of 40). The term scratch embossing was coined later by Rosen [18]. Scratch embossing is the process of dragging a stylus across the sheet while applying a one-to-three-pound force normal to the sheet. This plastically deforms the TDS material so that it rises in the wake of the stylus, leaving a permanent line in positive relief. BLV users can feel the line as they are drawing it, providing instant tactile feedback. The plastic deformation of the TDS causes it to change from colorless translucency to opaque white. This allows sighted people to easily see the lines, so that BLV users and sighted users can communicate graphically with one another.

The mechanics of the creation of these raised lines is not well understood. Close-up inspection of the tactile lines provides some insight into their creation, seen in Figure 1.1. As the line begins, the plastic lifts off the rubber behind the stylus until it reaches some critical length. At this point, the middle of the raised section of plastic buckles down towards the rubber. This breaks the raised portion of plastic into two separate bumps. This buckling process continues as the user proceeds to draw along the TDS. A close up view of a scratch embossed line can be seen in Figure 1.2 These behaviors are highly non-linear and rely on a number of factors, such as stylus geometry, rubber thickness, rubber hardness, downforce used, speed of drawing, the material properties of the TDS, and other possibly unconsidered factors. Possibly because of these complicating factors, there is no analytical model to predict the characteristics of a line. [1]

Figure 1.1: Example of scratch embossing.

[1] This paragraph is excerpted with minor revisions from a report the author submitted for ME 259 - Computational Solid Mechanics in May 2017

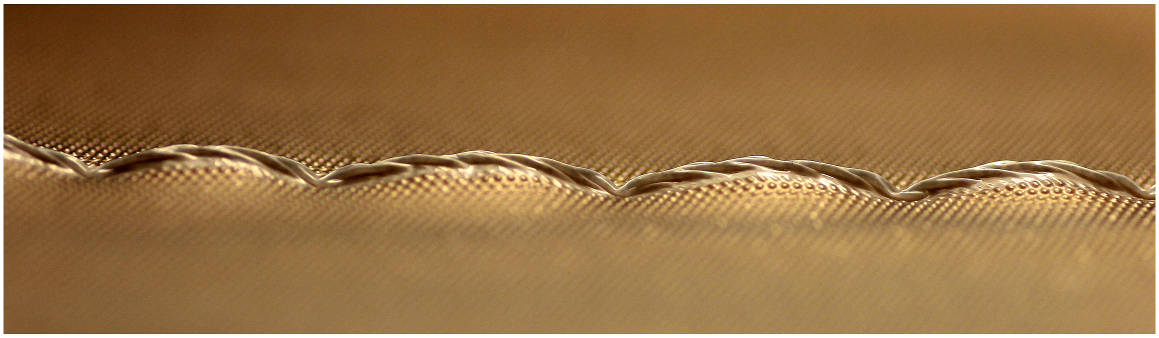


Figure 1.2: Example of scratch embossing.

It should also be noted that the phenomenon of scratch embossing is not unique to the TDS, or to the particular type of rubber backing. There is a range of materials that can be scratch embossed, including many plastics, and some aluminum foils. Different rubbers will also work, but they will affect the features of the lines created. It would be desirable to gain a better understanding of scratch embossing so that the rubber and sheet materials could be selected to produce raised lines with certain qualities. The author has done some preliminary work modeling scratch embossing using Abaqus finite element analysis software. Early results were promising but much more detailed study is required. The preliminary analysis can be found in Appendix A.

1.3 Commercial Realizations

Following the Sewell patent, there was relatively little commercial interest. There was a drawing tablet to hold the TDS in place for scratch embossing called the Sewell Kit that did not see widespread use. The American Printing House for the Blind (APH) sells a product called the Draftsman, which is also a drawing tablet that uses the tactile drawing sheets. Still, as of 2008 most BLV students had little to no experience with tactile drawing [16]. Part of the reason for this is that there is no automated, repeatable, digitally driven way to print a tactile graphic on the drawing sheets, and so they were mostly used by TVIs and parents to quickly sketch something for the BLV student. The other factor contributing to the infrequent educational use of tactile drawing is that students are rarely exposed to or taught tactile drawing during their early education. Without developing basic drawing skills at a young age, students are not equipped to start drawing in their geometry or calculus classes. Understanding these obstacles, the National Federation of the Blind (NFB), the largest organization of BLV people in the United States, made tactile drawing education and tactile literacy a priority in their national platform [17]. The

NFB also partnered with UVM CEMS faculty Rosen and Coleman to fund a Senior Experience in Engineering Design (SEED) project to develop the first printer for the production of tactile drawing sheets.

The deliverable from the SEED project (academic year 2010-2011), a proof-of-concept prototype of the tactile printer, had limited features but it was able to produce tactile graphics from digital files. Encouraged by the NFB, Dr. Rosen, Dr. Coleman, and Joshua Coffee (a member of the '10-'11 SEED team) founded E.A.S.Y. LLC in October of 2011. The work that E.A.S.Y. has since completed has generated a body of empirical knowledge about the uses and generation of tactile graphics which serves to guide and inform this project. Also, the author of this thesis has also been involved in that work in several capacities over the last four years.

Since its founding, the company has been awarded Phase I and Phase II STTR grants from NIH to develop and evaluate Alpha and Beta prototypes of the tactile printer, and to fund the work reported in this thesis. The Beta version has many more features than the Alpha, including Braille annotation, powered single-sheet feed, and the capacity to emboss lines with various characteristics under software control. The focus of this thesis project has been to expand the range of line characteristics that the printer can produce, primarily to enable it to emboss textures on the tactile drawing sheets. A variety of useful textures will allow tactile graphics to communicate information that would not be possible otherwise, the specifics of which are outlined in Chapter 2.

1.4 Literature Review

1.4.1 Engineering

Since the 1949 Sewell patent, there has been no published academic research into scratch embossing, either on the TDS described above or on any other medium. Furthermore, this is the first research to look into creating textures on this material. As a result, there is no directly relevant engineering literature.

1.4.2 Perceptual Psychology

There are similarly few publications in the literature of perceptual psychology directly relevant to the topic of tactile textures and their perception. What literature we have reviewed focuses on one of two topics: the characteristics and limits of human touch, and comparison of tactile perception of sighted subjects to that of BLV subjects. One of the foundational studies in this field, published by Heller in 1989 [13], concluded that, "No differences appeared between the sighted and the blind, [with regard to tactile perception] and it did not matter if touch were active or passive." A later study by Grant, Thiagaraja, and Sathian in 2000 [12], investigated the difference between the performance of a group of sighted subjects (with their vision occluded) and a group of blind subjects on tactile tasks by measuring how small a space between two tactile features could be detected. They found this "discrimination threshold" to be approximately 1mm, and they found that BLV people performed better than sighted people on some, but not all, of the tactile tasks. This conclusion was also supported by the findings of Alary, *et al.* in 2009 [6]. While this study found a slightly smaller tactile discrimination threshold, the results also suggested that sighted and blind individuals perform similarly well on tactile tasks, unless the task has features that the blind people are much more familiar with, such as Braille-like dots, in which case the blind subjects performed slightly better.

This avenue of study is the closest related prior work to our research, but it was being done with an entirely different mindset and goal, and consequently offers little insight for this thesis project. Rather than asking: "how small a difference can people perceive?", this design project must evaluate its outcome by asking "did this device produce textures that are different enough from each other that they are useful?" The key distinction between this project and prior research is that our textures were specifically designed to be as distinct as possible, so that our experiments represent an evaluation of the success or failure of the textures and the novel mechanism that produced them, not a characterization of our subjects. Thus, the limits of human tactile perception are of only peripheral interest to this work because the textures we produced were intentionally dramatically different from one another.

Prior studies did provide insight for the design and methods of the test used for subjective assessment of the textures produced in the course of this thesis project. For example, a study by Hollins and Risner in 2000 [14], suggested that texture perception is based on both "static touch" and "active touch." Static touch requires the subjects' hands/fingers to be stationary relative to the stimulus texture, whereas active touch requires relative motion between the two. The difference between tactile perception under these two conditions may be due to the minute vibrations generated by the motion of skin across a texture. This finding suggests that the subjects in this study should be allowed to move their hands over the sample textures to increase their opportunity to perceive characteristics and distinctions.

Another common theme in the prior studies is that subject performance can be influenced by familiarity with the tactile features used in the test, and that this effect can be somewhat mitigated by allowing the subjects to practice the test before data collection begins. Thus, all testing done in this project provided subjects with a practice period during which they could become familiar with the type of textures that they would be assessing.

The final insight gained from the reviewed tactile discrimination threshold studies [13] [12] is that when blind people and sighted people differ in tactile task performance, the differences are subtle. This recognition was applied to justify recruitment of sighted people as subjects for some early trials in this project (see Chapter 2) especially considering that the features of the textures assessed in those tests were much larger than the discrimination threshold. As a practical matter, testing with sighted subjects made available a much larger and more accessible population. Additionally, the cited studies found that the results of tactile texture assessment are influenced by seeing the texture. Based on this finding, all sighted subjects in our early trials wore sleep-shades to occlude their vision.

Chapter 2

Problem Statement and Preliminary Design

2.1 Design Objective

The objective for this project was to design a system (called the *Texture Creation System* or *TCS*) that would enable the Beta printer to be able to make *Useful* textures. Useful, in this context, means that the textures meet some or all of the following three criteria, so that they will be able to serve specific purposes on a tactile graphic:

2.1.1 Criterion 1: Distinct

The first criterion is that the textures need to be distinct from the blank sheet and from one another. In graphics for sighted people, this criterion can be met by filling areas with different colors, so readers can distinguish one area from another. Without discernible and distinct textures, it can be difficult for the "reader" of a tactile graphic to determine the difference between figure and ground. Line drawings can also often be ambiguous, such as a drawing of two concentric circles. It is not clear whether the drawing is meant to be a torus or a trajectory around a circular solid. This ambiguity can be eliminated by the incorporation of a texture to indicate which area of the drawing is meant to be "solid". Meeting this first criterion for distinctness is required for any texture to be considered Useful in the context of this project.

2.1.2 Criterion 2: Recognizable

The second criterion for Usefulness is that the textures be recognizable, meaning that two separate samples of a texture can be identified as the same. Meeting this criterion would significantly increase the utility of the set of textures. For example, they could be used for differentiation among areas on a map: water vs. plains vs. mountains; or for identification of areas bounded by curves on a graph. Recognizability of textures would also allow for the development of a set of conventions; just as a row of wavy lines is the standard way to represent an area as being a body of water, a particular texture that may feel wavy could become the standard for use on tactile maps. Meeting this criterion is required for any texture to be considered Useful, because it increases its range of applications.

2.1.3 Criterion 3: Vary in Degree

The third and final criterion by which the textures will be evaluated is their ability to vary in degree, that is: to have a texture be modified in some way so that it is still recognized as the same texture, but as feeling like "more" or "less." Textures that have this capability would allow for tactile graphics to include information about population density, temperature, pressure, and other properties that can vary across an area. In graphics for sighted people, this is often accomplished by varying the saturation of the color or the density of a dot pattern.

It is not required that all textures be able to vary in degree; however, some of the textures must in order for the overall set of textures to be Useful. Consultations with TVIs and the creators of the tactile content suggested that any particular graphic would have, at most, two textures that vary in degree. This determination was made because the small size of the TDS (∼8 in x 11 in) limits the number of textures that can be on the same sheet while maintaining clarity. So, if two of the textures can successfully vary in degree, then the overall set of textures will meet this third criterion.

For textures to meet these three criteria and thus be considered Useful, they will need to span a broad tactile range. The uniqueness of each texture will come from both the pattern of the lines that make up the texture, and from the physical characteristics of the lines themselves. Since the line patterns the printer can presently produce is virtually unlimited, the focus of the project will be to enable the printer to make lines with a wider variety of characteristics.

2.2 Constraints

This work is a part of a larger design effort, and as such, the overarching constraint is that the TCS must be compatible with the existing Beta printer. Compatibility specifically invokes the following constraints:

- Any mechanical components need to fit within the current size of the printer.
- No changes can be made to the Beta printer that fundamentally affect/hinder its operation.
- The TCS can not dramatically increase the projected price of the printer. The projected retail price of the printer is approximately $3000, and E.A.S.Y. management set a 5 percent limit for the additional parts cost of the TCS: $150.
- The TCS can not dramatically increase the time required to print a sheet. Prior to the TCS the typical printing time was approximately 90 seconds; the printer's developers have set an upper limit on additional time of 15 seconds per print.
- The TCS cannot noticeably increase the noise generated by the printer from its current level.

In addition, this work also adheres to several practical constraints typical of a master's project:

- The scope of work was constrained by funding.
- The project was limited to a time frame of a master's degree effort.
- This work was undertaken in conjunction with the other academic requirements for a master's degree.

2.3 Design Direction Decision

The first step in this design was to decide, in the most general mechanical terms, what the TCS would physically be doing. Essentially, it needed to be determined which physical variables the Beta 1 (the Beta printer with the addition of the TCS) would be able to control, variables that had fixed values in Beta 0 (the Beta printer, prior to the TCS). This decision was made experimentally by identifying what new variable had the largest impact on the range of line characteristics. The Beta 0 printer was able to control the downforce and the speed of drawing to produce a small variety of tactilely distinct lines. From experience and informal testing, it was clear that the geometry of the stylus tip has a large impact on the lines drawn, as seen in Figure (2.1). The other variable that had been observed to have an effect on scratch embossing is the temperature of the stylus. As the TDS (Tactile Drawing Sheets) are made from a thermoplastic with a glass-transition temperature of approximately 180 degrees Fahrenheit [20], it stands to reason that a stylus heated to this temperature or above would change the way that the plastic responds to scratch embossing.

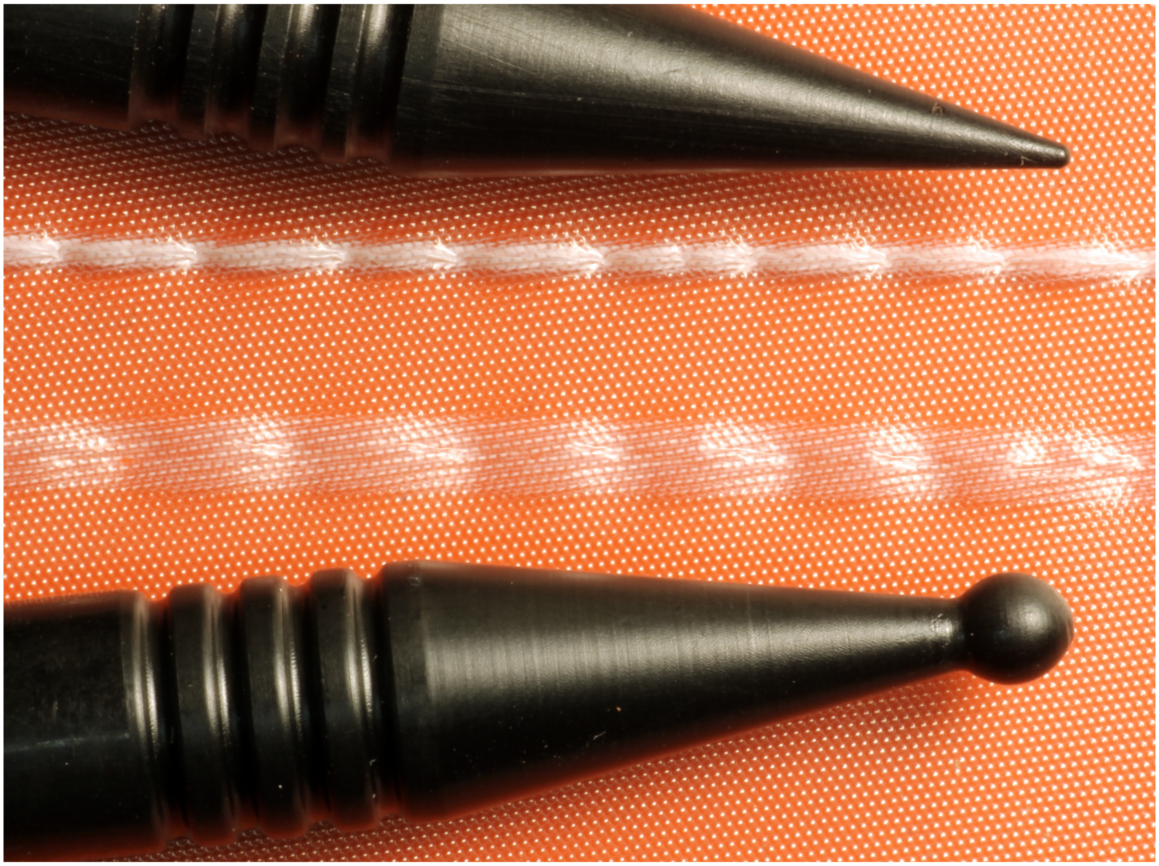


Figure 2.1: Two scratch embossed lines made with different tip sizes, shown next to each line.

It was also anticipated that there are other variables that contribute to the characteristics of the lines drawn, including the material of the stylus, the angle at which it is held, and how tightly the TDS is secured in place. In the course of exhaustive ad hoc trials it became clear that these variables do have slight effects on the lines, but the magnitudes of these effects were much less than variation introduced by changing the tip size or temperature. Additionally, changing the stylus drawing angle or the tension on the TDS often resulted in the ripping of the TDS. For these reasons, the primary design decision for the TCS was between designing it to be able to modify the drawing tip size or the temperature of the tip. To make this decision, the following experiment was performed.

2.4 Preliminary Psychophysical Experiment: Tip Size vs. Temperature

2.4.1 Background

The purpose of this experiment was to determine whether the TCS would be able to control the tip size or the temperature. To narrow down these variables, a set of texture test sheets (*Sheets*) was created to exemplify the texture variability generated by varying downforce and speed (the controlled variables in the Beta 0 printer) as well as the radius of tip and the tip temperature (proposed new control variables for the TCS). Downforce and speed were not held constant in this experiment because it was likely that these variables were coupled to the absolute and relative effects of changing the temperature and size of the drawing stylus.

For this preliminary experiment, each 3x3-inch texture sample was made from 13, 3-inch-long vertical lines, spaced 0.25 inches apart. This pattern was chosen because scratch embossed lines at or under 0.25 inches apart are not easily distinguishable as distinct lines. Thus, the assumption was made that this pattern would feel like a continuous texture, and would allow the range of subjective line characteristics produced by changing the physical variables to have the maximum effect on the perception of the texture samples.

These Sheets were scratch-embossed by hand, using a guide to keep the spacing consistent, a scale to regulate force, a metronome to regulate speed, and a temperature-regulated soldering iron to heat some of the stylus tips. Each Sheet was labeled with a sheet number and a coded number sequence, based on the combination of temperature, downforce, speed, and stylus used to create it. There were 34 total Sheets, some combinations of variables were omitted because they tore the TDS or did not created detectable scratch embossed lines. To save space, each Sheet included two textures. An example Sheet is shown in Figure 2.2.

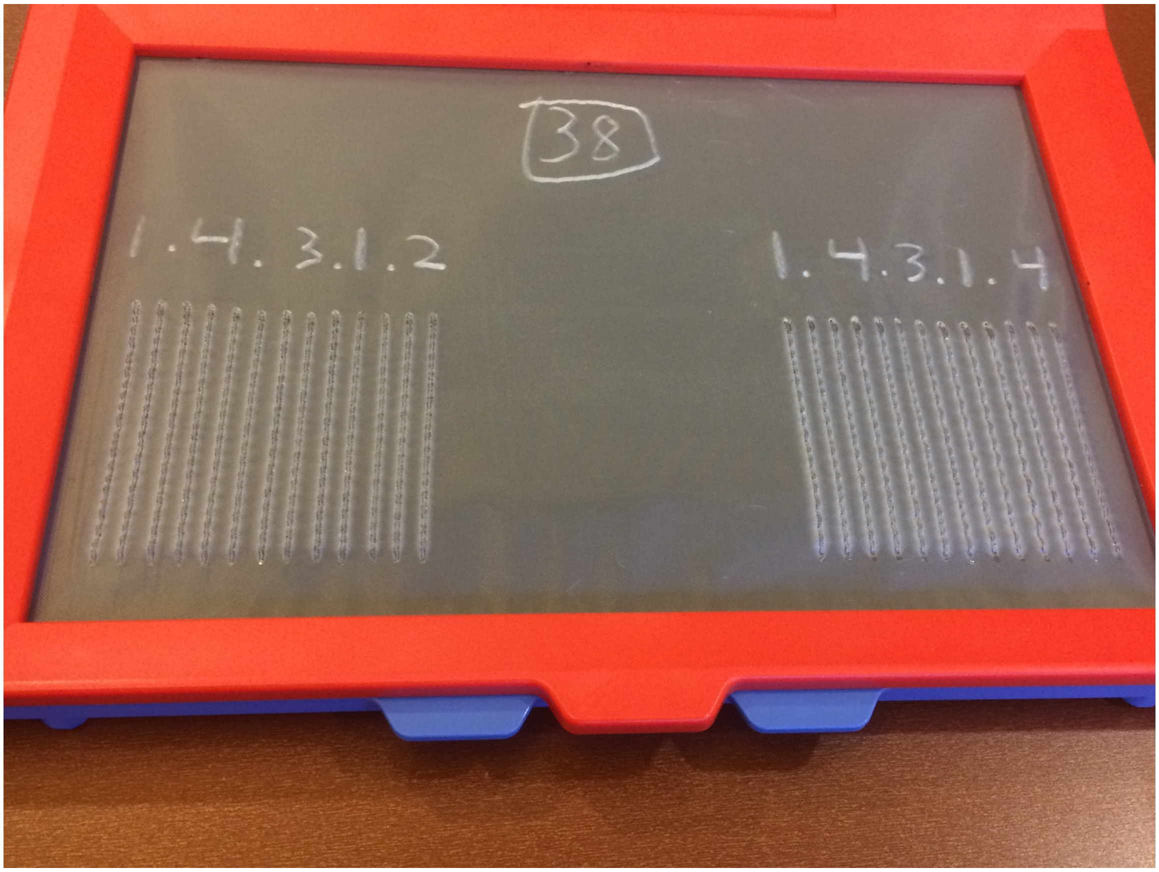


Figure 2.2: An example texture that was used in this experiment.

Four levels of downforce were used to make the textures: 1, 2, 3, and 4 pounds. These values were chosen because ~1 lb is the lower limit of downforce that will still cause tactilely perceptible scratch embossing to occur, and ~4 lbs is just below the downforce that tore the TDS. Speed was set to either 1.5 or 3 inches per second, chosen because 1.5 inches per second is the speed of embossing below which a drawing becomes unacceptably slow to print, and 3 inches per second was estimated to be the maximum speed of the printer. As speed has been observed to have less of an impact on line characteristics, only two values were chosen to reduce the time this experiment would take.

Five different styluses were used in this experiment, chosen based on the ad hoc testing. Two of those tested were the tips of the double-ended stylus that APH sells for scratch embossing: a 4mm ball (*APH Ball*) on one end and a rounded cone measuring ~1.0mm where the tip of the cone transitions to a sphere (*APH Sharp*) on the other. The third stylus was the one that E.A.S.Y. LLC makes for freehand drawing, in the shape of a rounded cone, measuring ~1.8 mm. The final two stylus tips used were from a Weller soldering iron, both rounded cones, one modified to measure ∼1.3mm (*Shop-made Soldering Tip*) and one a stock size of 1.5mm (*Weller Tip*).

The two styluses that could be heated made textures at ambient temperature, 180 °F, 200 °F, and 240 °F. These four temperatures were chosen because 180°F is the glass-transition temperature of the TDS, 200°F is between that and the melting point of ∼212°F, and 240°F is above the melting point.

Two words were chosen to represent the particular subjective dimensions on which subjects would be asked to judge the texture samples: *Roughness* and *Density*. Each word was meant to be understood as it would be in common English usage. It was expected that Roughness would be understood by subjects as an assessment of the feature geometry in the Z-direction (out of the plane of the sheet), so that a texture composed of higher, sharper features would be rated as rougher than one with lower, more rounded features. Density was clarified for subjects as the fraction of the area that was occupied by features, relative to the area that is "blank." Since all textures had the same center-to-center spacing between lines, the variation in responses in Density was expected to mostly be due to different line widths, because wider lines would leave less blank space in a texture. Thus, it was expected that texture with thin lines would be rated as less dense than a texture with thicker lines, i.e. that subjects' Density ratings would be driven primarily by distribution of line features perpendicular to the direction of the lines, the X direction. It is also likely that these two perceptual dimensions, Roughness and Density, which we were assuming to be independent variables, are in fact linked. This was one of the key assumptions that would need to be challenged if the TCS had not met its design goals.

2.4.2 Methods

As this was just a preliminary experiment, five subjects were chosen based on ease of access. All the subjects were sighted, so they were required to wear a sleep shade during the entirety of the experiment to prevent the appearance of a texture from influencing responses to its feel. As discussed in the Literature Review, sighted subjects have comparable tactile skills to those of BVI people, especially when given opportunity to practice and when the features are not similar in feel to Braille if the subject is a Braille user. Thus we made the assumption that recruiting sighted subjects for this preliminary experiment would provide results that would compare acceptably well to data gathered from BVI people.

The subjects were instructed that they would be providing a numerical ranking from 1 to 5 for the *Roughness* and the *Density* of each texture. Roughness and Density were explained to the subjects using the language discussed in the previous section. The scale for both Roughness and Density was anchored with a *Calibration Sheet*, seen in Figure 2.3. This sheet included a texture that was described as *maximum Roughness*, created with a sharper stylus and a higher downforce than was used for any of the textures in the experiment. This created a higher Roughness texture than any of the samples used in the test. Subjects were presented with this texture and taught that it is a 6 on the Roughness scale, meaning that this texture is just beyond the scale that they would use to evaluate the other textures.

The Calibration Sheet also included a *maximum Density* texture which had twice as many lines per area as the textures used in the experiment, making for a very high number of features-per-area. Subjects were told that this texture was a 6 on the Density scale. They were also told that a 0 on the scale for both Density and Roughness was the feel of the blank sheet. Giving the subjects these references on either end of the scale was done in an attempt to standardize it, so that the subjects would all have approximately the same expectation of what mid-range Roughness and Density values (ratings of "3") might feel like.

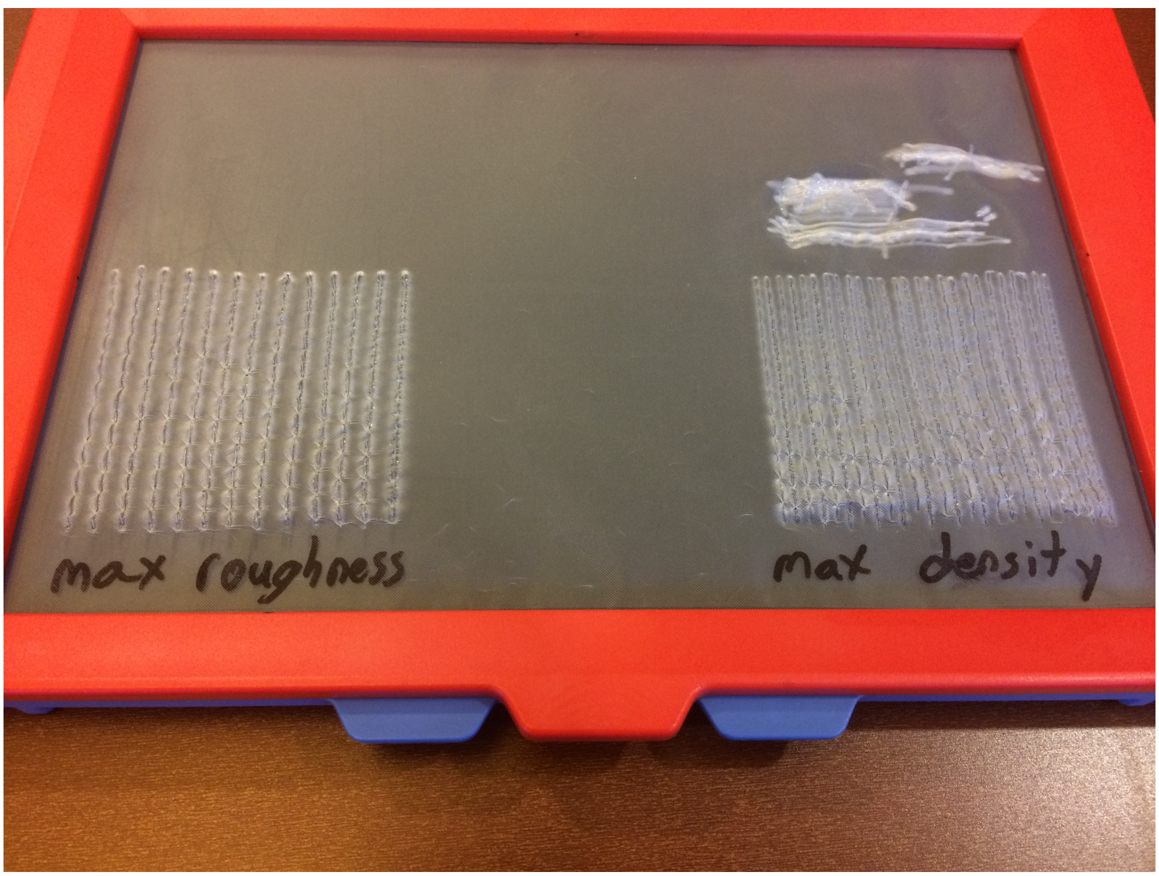


Figure 2.3: The calibration sheet, showing maximum Roughness (left) and maximum Density (right).

Following the discussion of Density and Roughness, each subject was allowed to feel a random sample of the Sheets to get a sense of the range of Roughnesses and Densities that they would be feeling during the experiment. For the actual experiment, the textures were presented to the subjects in a random order, with the same order used for all subjects. The subjects were instructed to respond with a numerical rating for the Roughness and then the Density of each texture sample. They were given as much time as they wanted to scan (actively touching and feeling a sample with moving fingertips) each texture before responding. After every ten textures, the subjects were presented with the Calibration Sheet again, in an attempt to maintain consistent subjective scaling during the course of the experiment.

2.4.3 Results

The data presented below were collected from the five subjects and analyzed in MATLAB®. The goal of this analysis was to determine what pairs of Roughness value and Density value were reported by each subject across the full set of Sheets - in order to see what range of subjectively different textures could be produced from the entire available range of the four independent variables (downforce, speed, tip size, and tip temperature) values.

Following this, the data were separated into subgroups, according to which variables were varied to generate the data. These subgroups could then be compared to each other, to determine which variable was able to produce a wider range of textures. Each could be compared to the full set of responses to see what amount of the full range of Roughness and Density perception was lost in the subgroup. This analysis was designed to establish which new printer variable produced the largest number of extreme reported values of Roughness and Density. The extreme responses were of particular interest because it was assumed that they would be correlated with the textures that were most unique, and therefore most likely to meet the criteria for being Useful.

Texture Spread Plot Explanation

Our data is presented below in *Texture Spread Plots* (or *TS Plot*), a way to graphically show what range of Roughness and Density combinations (R, D) were reported within a subgroup of data. The size and color of each circle represents the number of subjects who found, for some combination(s) of independent variable values, the particular combination of Roughness and Density. The TS Plot in Figure 2.4 displays all of the data collected in this experiment. There are four circle sizes, showing that 2 (blue), 3 (magenta), 4 (green), or 5 (black) of the subjects found the combination of Density and Roughness. It can be seen, for example that all five subjects found at least one texture that they rated as having a Roughness of 1 and a Density of 4; this is shown by the largest size black circle. In contrast, only two subjects found a (R, D) combination of (3,2), shown with the smallest size blue circle.

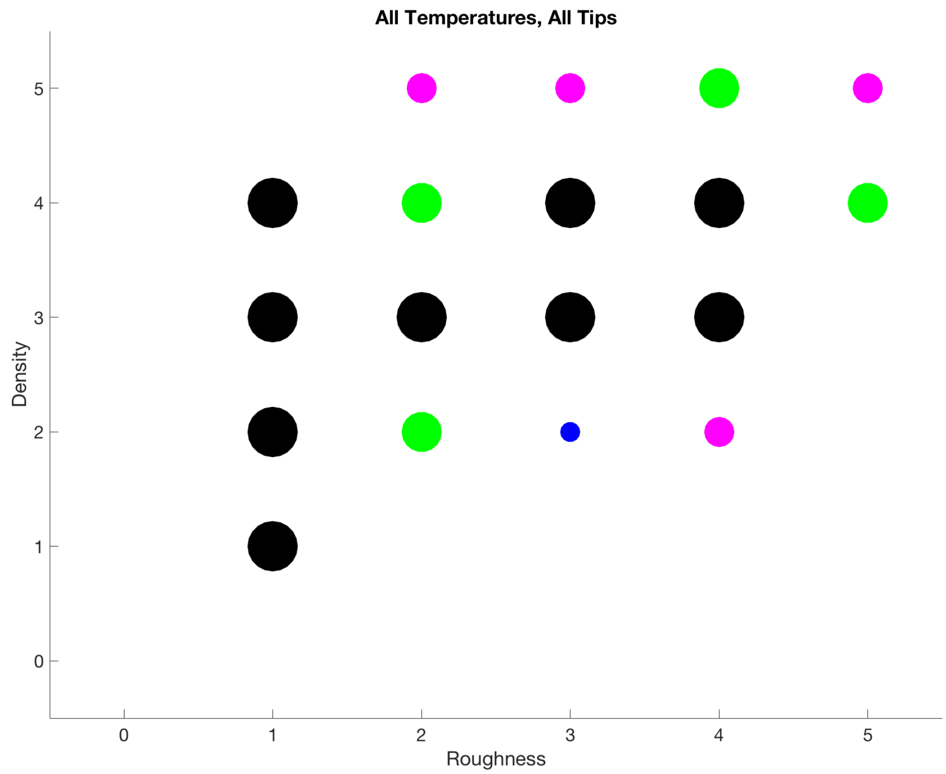


Figure 2.4: TS Plot displaying the spread of data for all temperatures and all tip sizes. Sum of perceived (R, D) values = 75.

No circle is shown if only 0 or 1 out of 5 subjects found that combination. This amounted to defining a threshold: if fewer than 2 out of 5 of subjects experienced a particular Roughness-Density combination, the range of available independent variable values was judged as "unable" to produce that experience of Roughness and Density. It is important to note that if a subject found a particular (R, D) combination more than once, it does not increase the size or change the color of the circle. In these TS Plots, stylus downforce and drawing speed were both allowed to vary over their full range of values.

Findings

The Texture Spread Plot generated using the data collected for all textures created with an *unheated* stylus can be seen in Figure 2.5. This graph shows the range of Roughness and Density combinations that could be created by changing only the stylus size, with all styluses at ambient temperature. A third Texture Spread Plot, seen in Figure 2.6, was created using the data from textures created with a single, intermediate-size stylus tip (Weller Tip), used at a range of temperatures. This graph shows the range that could be created with a constant tip size and variable temperature. Comparison of these two plots provided an experimental basis for our central design direction decision: whether the TCS should be designed to change the tip size or the temperature, in order to be able to make the widest perceived range of textures.

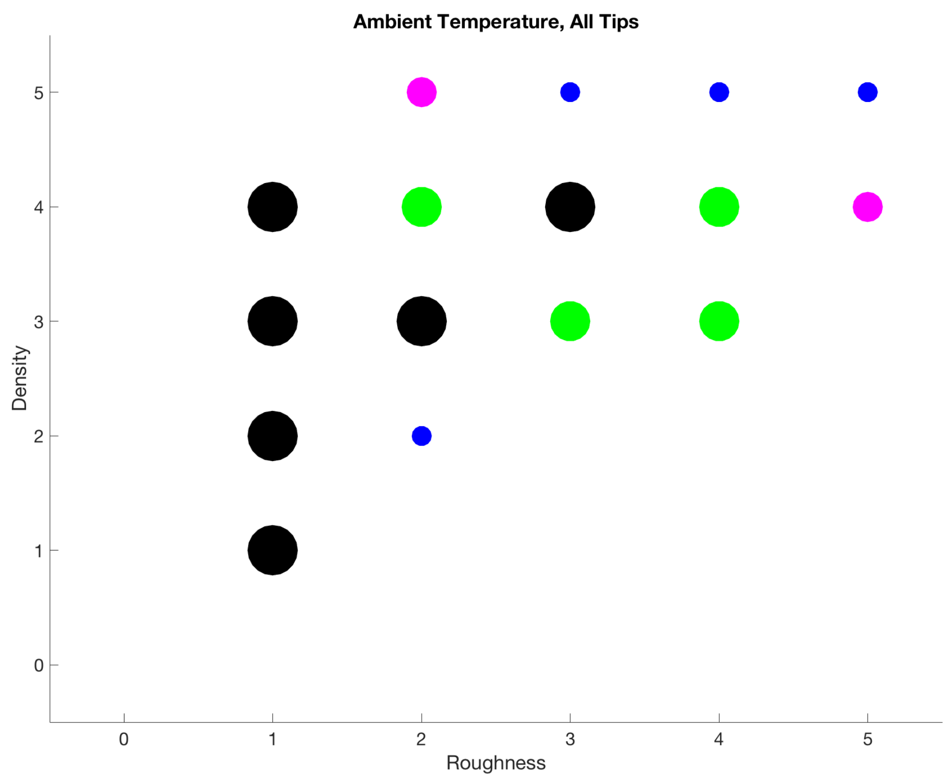


Figure 2.5: TS Plot displaying the spread of data for all tip sizes at ambient temperature. Sum of perceived (R, D) values = 60.

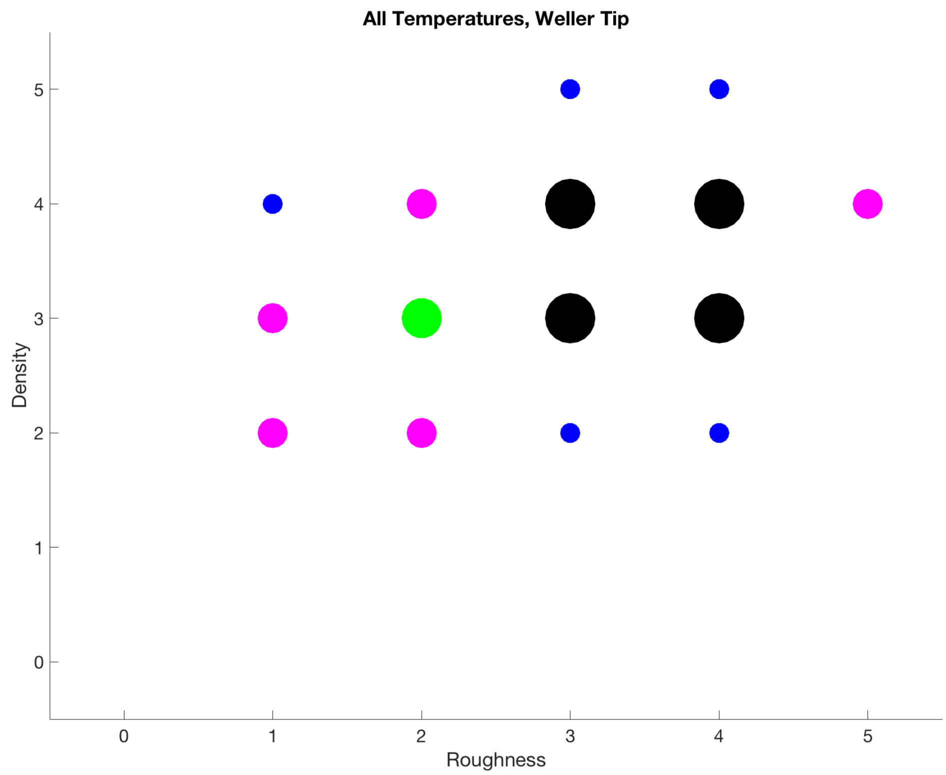


Figure 2.6: TS Plot displaying the spread of data for all temperatures and one tip size. Sum of perceived (R, D) values = 49.

2.4.4 Discussion

One way to quantify and compare these plots was to take the sum of all the values in the plot, where a "perfect score" would be 125, a TS Plot where all five subjects found all 25 combinations of Roughness and Density. In the full data set (Figure 2.4), the actual sum of (R, D) perceptions was 75. In this discussion, each subgroup will be compared to the entire body of data (sum of 75) to see what range of (R, D) perceptions remains in the subgroup when the effects of one of the new independent variables was eliminated. This sum gives a measure of the overall range of textures found in the subgroup of data, but no indication to the distribution or location of these textures on the Roughness/Density axes. 80 percent of the overall range of textures remained when only considering the subgroup of those made without increasing the temperature, Figure 2.5 compared to Figure 2.4. Only 65 percent of the range of textures remained for the subgroup of textures made with one tip across the full variance of temperatures, Figure 2.6 compared to Figure 2.4.

In addition to just considering the overall range, it was particularly important to investigate the extremes. As previously discussed many of the textures feel very similar to one another, so those that were given extreme ratings of Density and/or Roughness (a response of 1 or a 5 for either descriptor) were assumed to be the most unique feeling. The two subgroups were again compared to the entire body of data, which had a sum of extremes equal to 37. Textures made by just changing tip size (constant temperature) retained 86 percent of the extremes, while textures just made by changing temperature (constant tip size) only retained 47 percent of the extremes.

2.4.5 Conclusions

The numerical data, in particular the analysis of the extreme responses of Density and Roughness, strongly suggested that designing the TCS to be able to vary the tip size would enable a wider range of textures than if it were to vary the temperature. Modifying the stylus tips maintained 86 percent of the extremes, while modifying the temperature only maintained 47 percent of the extreme values. As the extremes are assumed to be the textures most likely to be Useful, it was considered critically important that the design of the TCS enable it to create these textures.

The anecdotal reactions collected during the experiment also support this conclusion. The subjects were asked to comment on any textures that felt qualitatively different in some way; the four subjects who made any comment singled out the textures made with the largest stylus (APH Ball). Three subjects said that these textures felt "bumpy" and one said that they thought that this texture was made from individual bumps rather than from lines. One subject made a comment about one of the textures being "bumpy" and "soft," and later in the experiment, they were presented with a texture made with the same parameters (except speed, which caused the smallest variation) and they said that they recognized it from before, and that it felt the same as the "bumpy" and "soft" texture from before. Additionally, none of the subjects singled out textures that were created by varying the temperature of the stylus. This is consistent with the conclusion from the numerical analysis, that the design of the TCS will enable it to vary the size of the tip(s) used for drawing.

Determination of Useful Tip Size Range

To help determine which tip sizes should be included in the TCS, Figure 2.7 shows TS plots, broken into subgroups for each of the five tip sizes. It should be noted that for data subgroups this small, there are not enough data points to make well-justified determinations, so the tip-size decisions below were based in part on the reported data, and in part on the E.A.S.Y. research team's extensive observations of tactile graphics users. The graph for the APH ball stylus shows the largest range, and it created textures that people singled out as distinctly different from the others. Thus, one of approximately this size should be included in the TCS. In order to comply with the compatibility constraint, the TCS will also need a standard drawing tip for making lines that are not necessarily meant to be part of textures, similar in size to the E.A.S.Y. freehand stylus. Experience suggests that a third stylus, similar in size to the APH sharp stylus or the shop-made soldering tip, should also be included. This stylus tip should be as small as is practical, without ripping the TCS, so that it would allow the TCS to create textures with unique-feeling low Density (narrow), high Roughness (sharp) lines. These three stylus tips should enable the TCS to create a wide range of Roughness/Density combinations, and therefore many tactilely distinct textures.

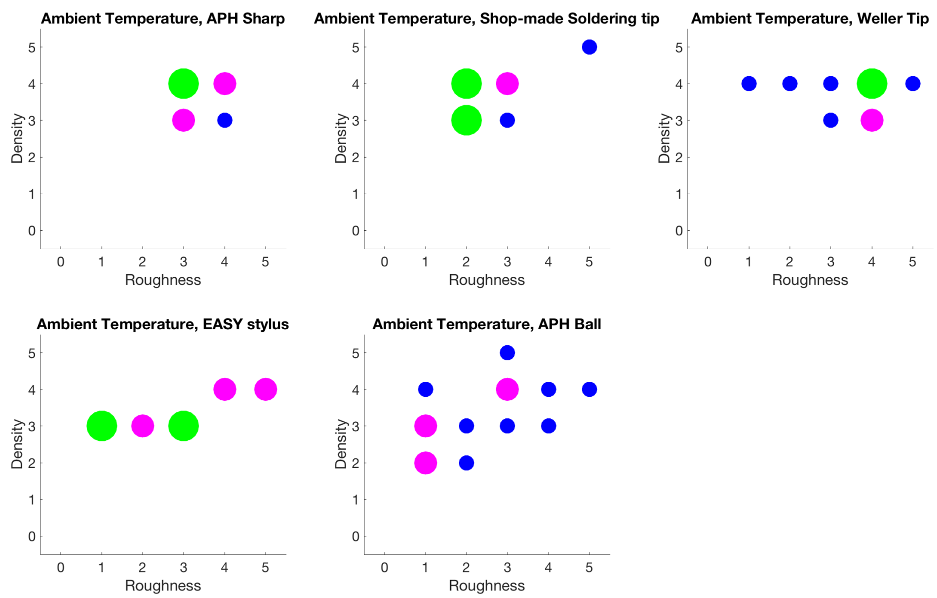


Figure 2.7: Graph displaying the spread of data for each stylus, all at ambient temperature.

Chapter 3

Design, Build, Evaluate

3.1 Beta 0 Design

The design of the TCS was directed toward modifying, replacing or supplementing the drawing system of the *Beta 0* printer. When this project was begun, the Beta 0 used a gantry system (*XY Transport System*) to move a *Drawing Carriage* in the X and Y directions over a platen that supports a TDS (Tactile Drawing Sheet), as seen in Figure 3.1 below. The scratch embossing mechanism was supported on the Drawing Carriage, seen in Figure 3.2. This design used a stepper motor to actuate the stylus in the Z axis by moving a precision ground (± 0.0005 in tolerance) aluminum rod through a sintered bronze bushing. The *Z Motor* rotated the *Spring Arm*, a 3D printed piece which drove one arm of a helical spring. The other arm of the spring was contained in a slot in the *Stylus Arm*, another 3D printed element which drove the stylus through a pin-in-slot mechanism. As the Spring Arm was rotated by the motor, it could either lift the stylus off the drawing (positive-Z rotation), or put the stylus into forceful contact with the TDS and the stiff elastic support pad underneath it (negative-Z rotation). When the motor drove in the negative-Z sense, the angle between the Spring Arm and the Stylus Arm determined how much the spring was distorted (wound up), and thus how much force was applied to the TDS for scratch embossing.

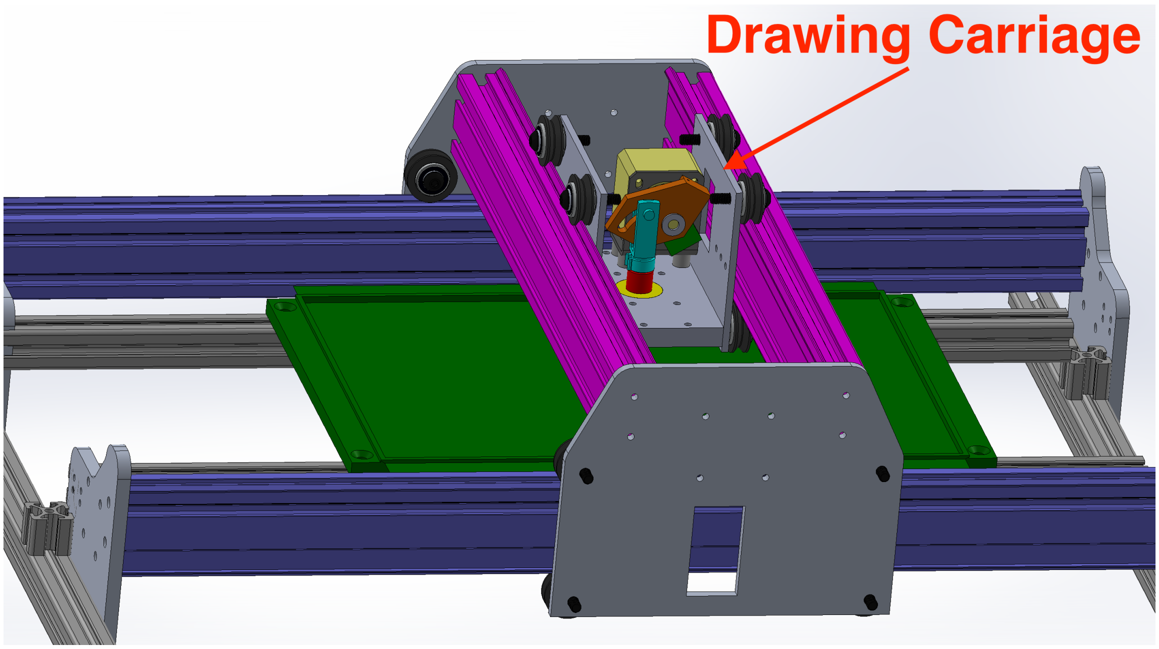


Figure 3.1: SolidWorks® model of the XY Transport System for the Beta 0 printer.

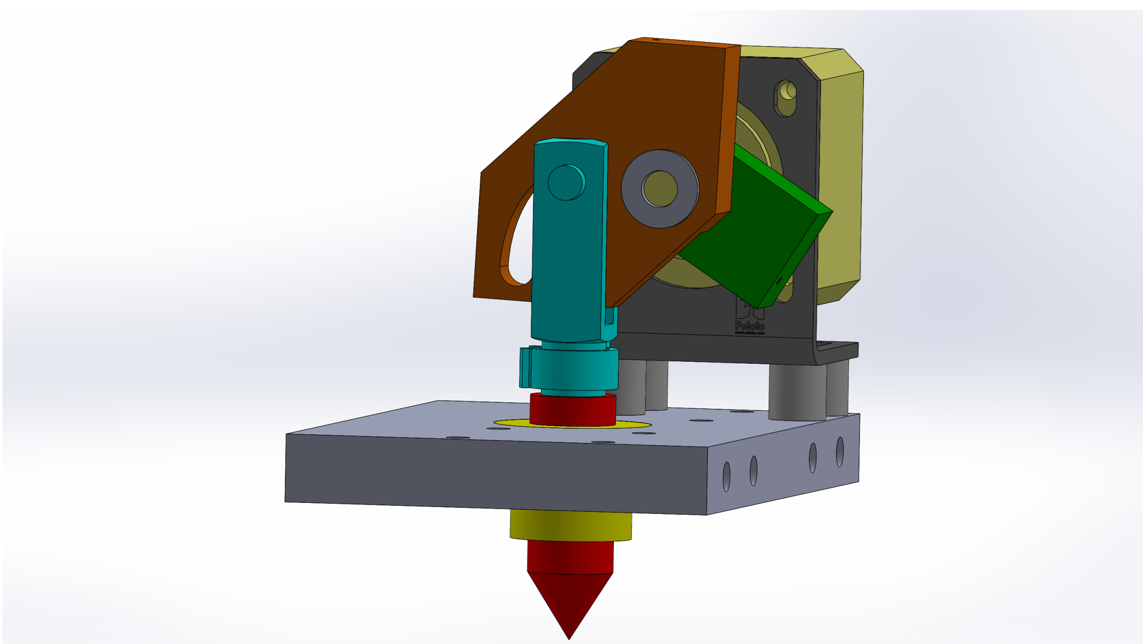


Figure 3.2: SolidWorks® model of the drawing system for the Beta 0 printer. In this model, the aluminum stylus is shown in red, the brass bushing is yellow, the Spring Arm is green, and the Stylus Arm is orange.

The following two Limitations were imposed on the TCS design process by the constraints (see Section 2.2) that these core functions be maintained:

1. The capacity to produce the controlled negative-Z force required for scratch embossing.

2. Sufficient strength, stiffness and absence of backlash to withstand the significant side-loads produced during XY translation without affecting line quality and drawing accuracy. From previous experiments, scratch embossing had been shown to produce a reaction force parallel to the line being drawn as high as 3 lbs. The stylus design in the TCS needed to be able to bear this load without significant displacement of the tip, either from insufficient stiffness, or from excess play in the system. Thus, any changes to the precision rod and bushing design needed to maintain the Beta 0 printer's capacity to function under these planar loads.

3.2 Conceptual Design

Once it was determined that the TCS would function by changing the tip size (see Chapter 2) an evaluation of the various methods of accomplishing this change was undertaken. This was done by identifying and considering various categories of designs for plausibility, looking to see which categories had obvious flaws or drawbacks that eliminated them from inclusion in the detail design stage. This determination was made if the category would fail to meet any of the constraints in Section 2.2, including the Limitations discussed in the previous section. For clarity, this thesis will track the refinement of design category through a series of flowcharts, the first shown in Figure 3.3

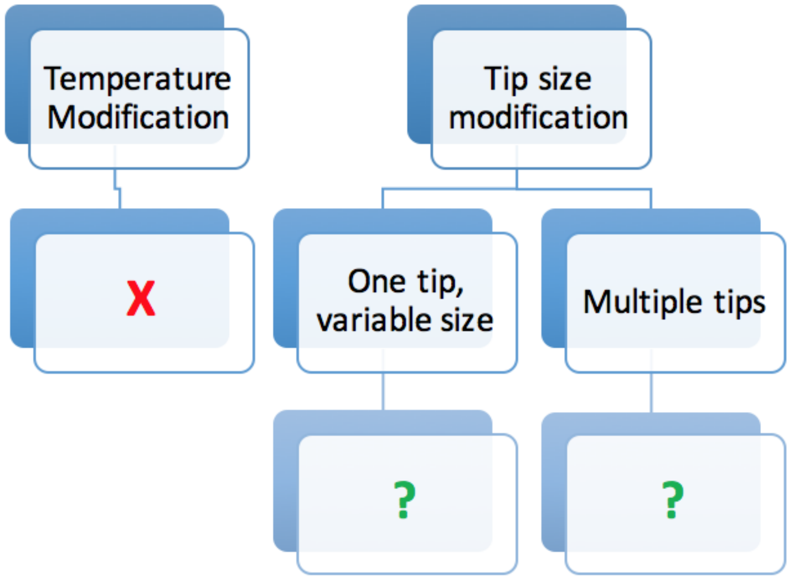


Figure 3.3: Flowchart showing the first decision node. The red X signifies a design path that was not pursued, and the green question mark signifies a path that merited further exploration.

3.2.1 Variable-Size Tip vs. Multiple Tips

The highest-level node in the design concept tree distinguished between those that involve one tip designed to change its size, and those that involved multiple, fixed-size tips that can be mechanically chosen for drawing as part of printer control. A single, variable tip presented some advantages because it could be accomplished with fewer parts and it would allow continuous tip size change, rather than a limited set of discrete sizes. This type of design could have been actuated hydraulically, with the tip being filled or emptied to change its size; or mechanically, with pieces that folded or deployed to change the size. Both the hydraulic and the mechanical designs had unavoidable drawbacks that prevented them from being pursued. The hydraulic type design would have required very high pressures to ensure that the tip did not deform significantly while drawing. As drawing causes some amount of wear on the drawing tip, it could potentially burst and cause failure of the system and damage to other components on the printer. The drawback of the mechanical systems for a variable size tip was that they would require very small (less than 1mm) parts which would be expensive to fabricate to the high tolerances and surface finish that would be required. These small parts would also be more likely to break under expected loads. In addition, tips comprised of multiple sub-millimeter parts, each with edges in contact with the TDS, would be more likely to cut or tear the TDS. For these reasons, a decision was made to pursue and further refine the other category of designs: those with multiple drawing tips, each of a different size. This decision advanced the design flowchart to the next step, as seen in Figure 3.4.

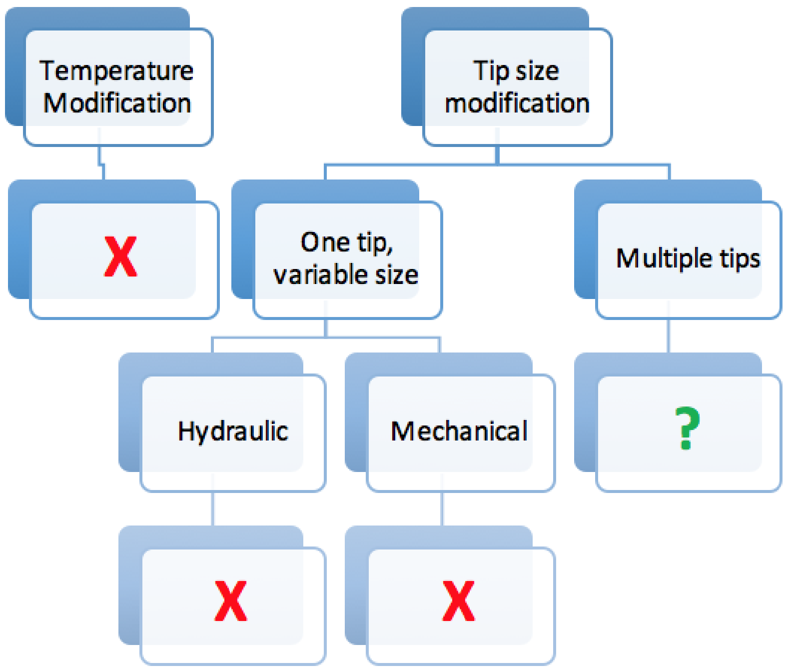


Figure 3.4: Flowchart showing second design category decision, where the red X signifies a design path that was not pursued, and the green question mark signifies a path that required further exploration.

3.2.2 Multiple Tip Design Selection

The next step in the refinement of the design was to determine the method by which the different tips would be mechanically selected for drawing. At this stage, the mechanical details for potential designs were considered and sketched. Early sketches of some of these designs can be seen in Figure 3.5. These designs were separated into the following three categories: Multiple Downforce Assemblies; One Downforce Assembly, Selectable Tips; and One Downforce Assembly, Replaceable Tips.

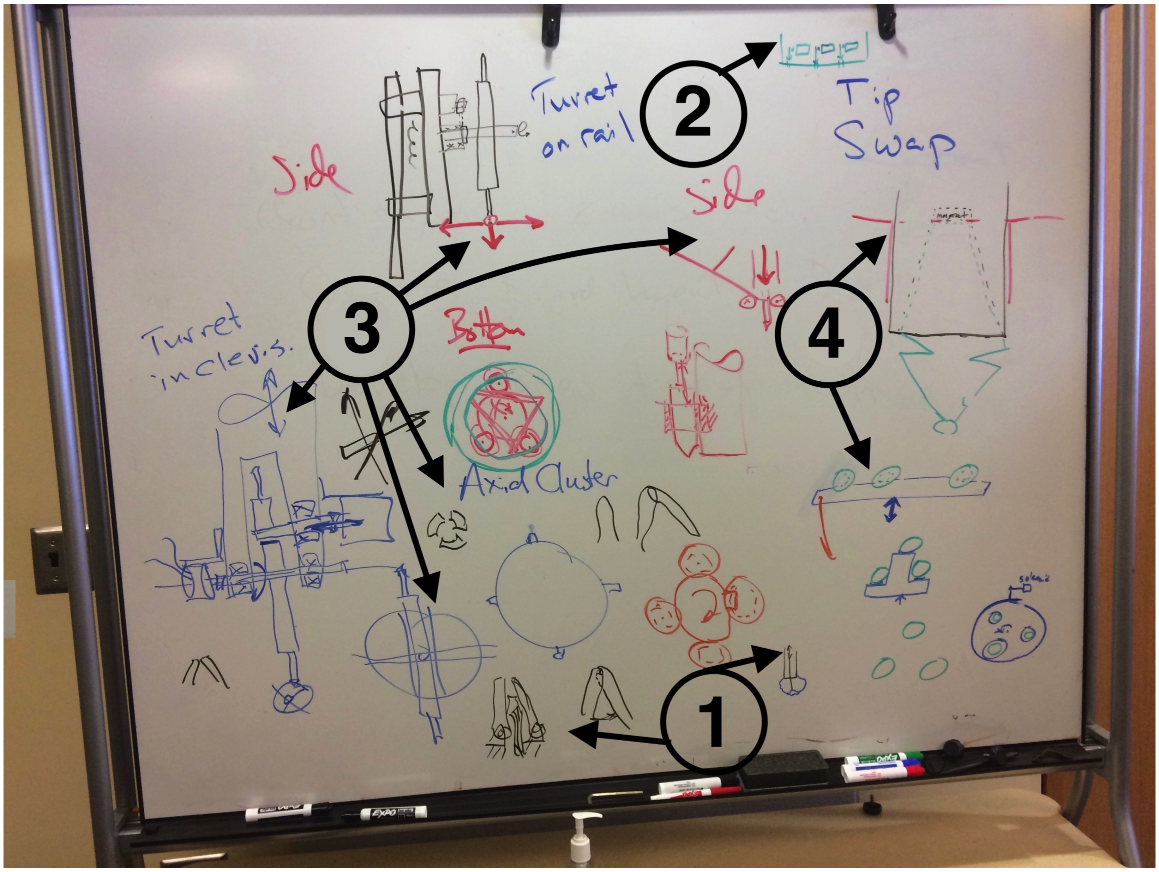


Figure 3.5: Early sketches of conceptual designs, labeled by category.
1: One Tip, Variable Sizes
2: Multiple Downforce Assemblies
3: One Downforce Assembly, Selectable Tips
4: One Downforce Assembly, Replaceable Tips

Multiple Downforce Assemblies

The first and most straightforward approach to have more than one drawing tip was to replicate the Downforce Assembly on the Beta 0 printer for each tip, sketched in Figure 3.6. Given the constraint of not increasing the size of the Beta 0, this approach would have allowed at most two drawing tips. Since the Preliminary Psychophysical Experiment suggested that at least three tips were needed for the TCS, this design concept was eliminated.

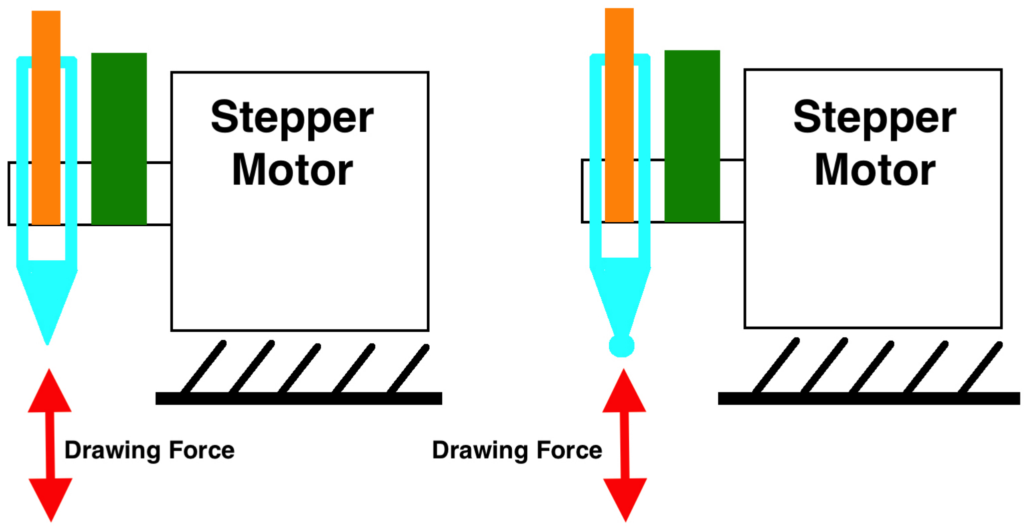


Figure 3.6: Sketch of Multiple Downforce Assembly design.

One Downforce Assembly, Selectable vs. Replaceable Tips

At this stage in the design process, there were two remaining categories of design to consider: *Selectable Tip* designs and *Replaceable Tip* designs. Both categories would use a single Downforce Assembly. The Selectable Tip designs would use a *Stylus Selector*: a mechanism that interposes one of several tips between the drive mechanism and the TDS. Some of these designs would rotate the desired stylus into place, similar to a traditional microscope lens turret. Other forms of this design type had the styluses in a row and would move them linearly into place for drawing. These are sketched in Figure 3.7 and Figure 3.8.

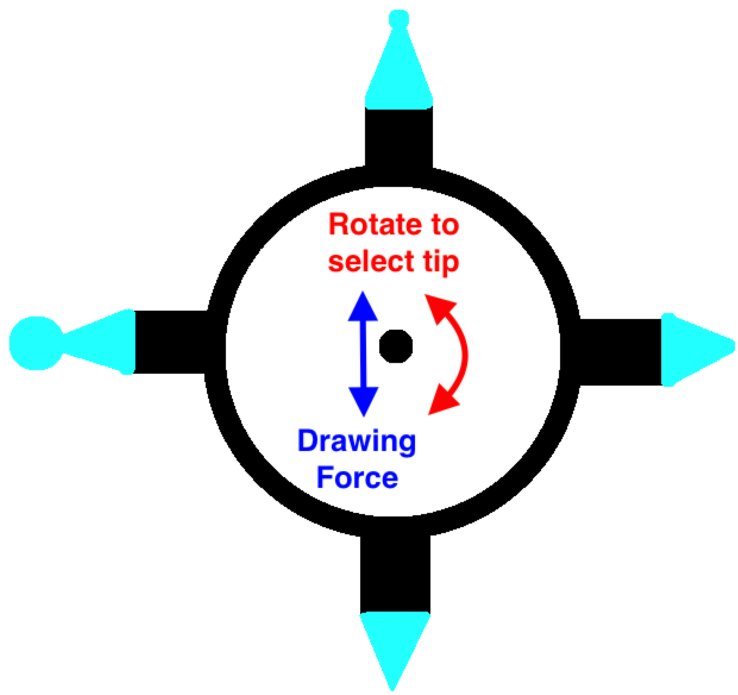


Figure 3.7: Sketch of Selectable Tip design, rotational arrangement.

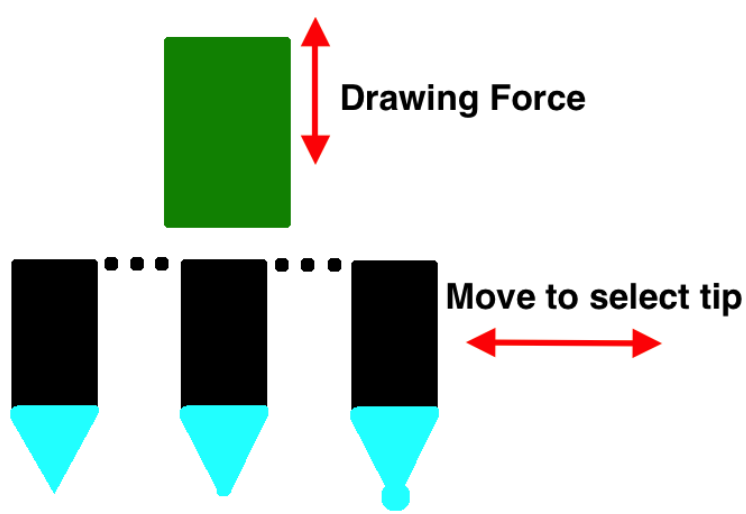


Figure 3.8: Sketch of Selectable Tip design, linear motion arrangement.

Replaceable Tip designs would use a method of exchanging the tip of the stylus by attaching/detaching parts. This could have involved either of two approaches: tips with a taper that mated with a correspondingly tapered receptacle in the drawing assembly, or tips that screw into a threaded receptacle in the drawing assembly. In either case, the unused tips would be stored in a *Tip Garage* when not in use. These are sketched in Figures 3.9 and 3.10.

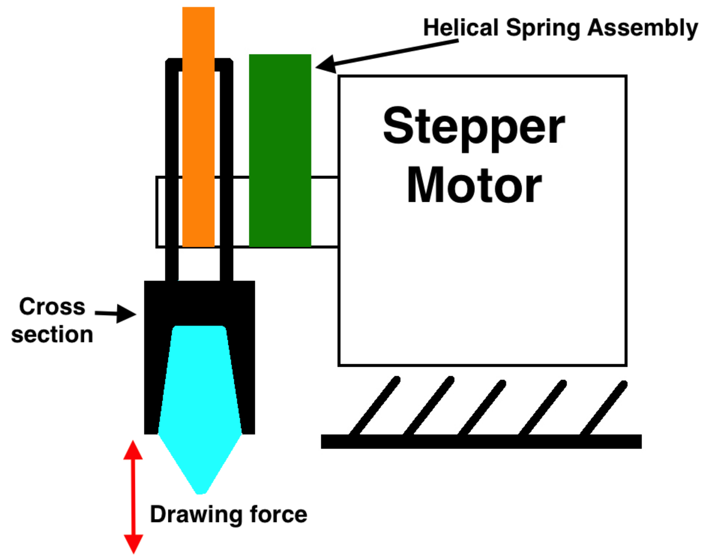


Figure 3.9: Sketch of Replaceable Tip design with tapered tips.

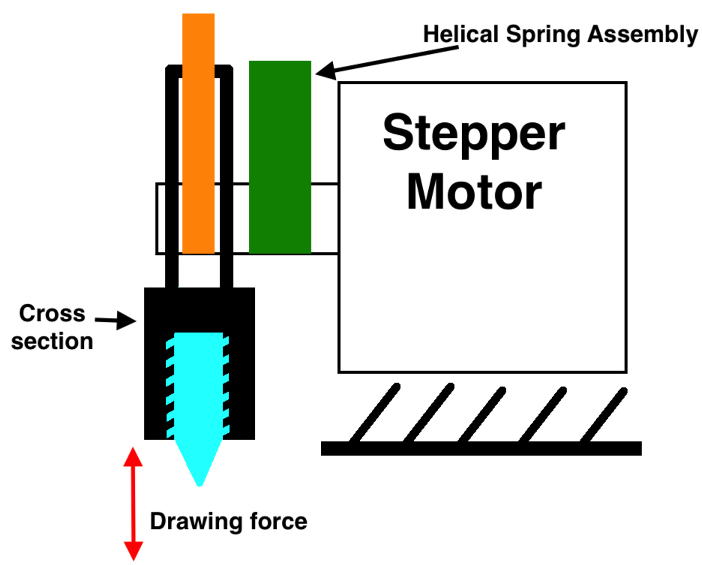


Figure 3.10: Sketch of Replaceable Tip design with threaded tips.

The comparison between these two categories of designs is summarized in the Pugh Chart in Figure 3.11. The desirable attributes in grey at the bottom of the chart were factors that were considered during this process, but that did not obviously favor one design category or the other.

		Design Category	
Desirable Attribute	**Weighting factor**	Selectable Tips	Replaceable Tips
Speed	2	1	
Resistance to Displacement from Side-Load	3		1
Smallness	1		1
Simplicity of Additional Mechanism	2		1
Triviality of Accidental Failure	3	1	
Consistency of Alignment	2		1
Desirability of Location of Additional Mechanism	2		1
Reliability	2		
Durability	2		
Ease of Maintenance	1		
Quietness	2		
Low Weight	2		
Economy	2		
	Totals:	5	10

Figure 3.11: Pugh Chart of Selectable Tip designs vs. Replaceable Tip designs.

The main issue with Selectable Tip designs was that whatever method they used to move the tip into place would introduce one or more new degrees of freedom of movement into the Downforce Assembly between the motor and the TDS. In some drawing directions the side-loads generated when drawing would have been in line with the axis of motion of the Stylus Selector, and this mechanism would have needed to resist those forces. As the side loads involved in scratch embossing can be as high as 3 lbs, the component used to actuate the Stylus Selector would have needed additional latching mechanisms to resist them. This was a significant issue in these designs because maintaining the low displacement of the drawing assembly is the second Limitation, thus its high weighting factor in the Pugh Chart. The main deficit of Replaceable Tip designs relative to Selectable Tip designs was that in the case of mechanical failure, they could have been expected to have more severe consequences; as the Replaceable Tip designs involve parts being attached and detached, they may detach in undesirable circumstances/locations. Replaceable Tips designs were also expected to be slower than Selectable Tips.

One positive feature of the Replaceable Tip designs was that they would not add significant new mechanism to the Drawing Carriage. Nearly all of the bulky additional mechanism needed for the Replaceable Tip designs, the Tip Garage in particular, could be positioned in one of several separate locations in the printer frame. This was considered a desirable feature because there was little room to add components to the Drawing Carriage of the Beta 0 without increasing the size of the printer, and because adding mass to the Drawing Carriage could have impaired the dynamic response of the carriage or required higher-torque X and Y drive motors. In contrast, the additional mechanism required for the Selectable Tip designs would be entirely located on the Drawing Carriage.

Another key benefit of Replaceable Tip designs was that they did not appear likely to lose any precision relative to the Beta 0. The precision aluminum rod, called the *Stylus Shaft* in this design, and the brass bushing would still have the same level of precision; and as this design required these components to be larger, they would have greater resistance to bending. Since either the threads or the mating taper would be internal to the Stylus Shaft, the resistance to side loads of the Beta 0 would be maintained.

Based on the above comparison of the two candidate design categories, it was decided to move forward with the Replaceable Tip designs and not with the Selectable Tip designs. This conclusion is represented in the completed Design Decision Flowchart, shown in Figure 3.12.

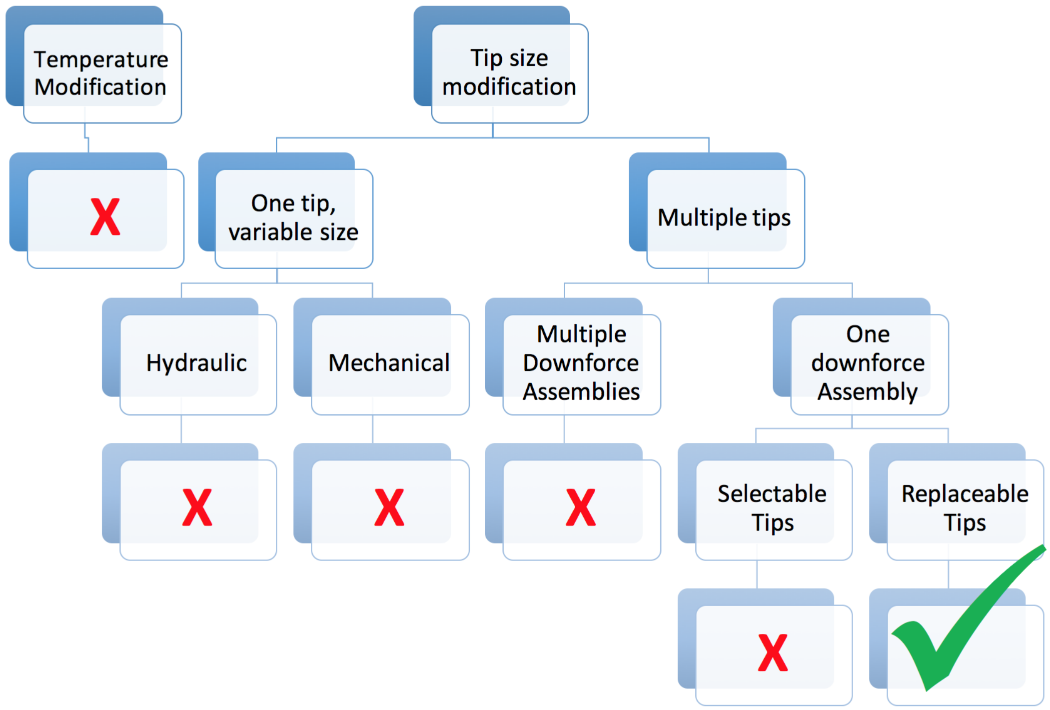


Figure 3.12: Flowchart showing full design category decision. The red X signifies a design path that was not pursued, and the green check mark shows the design category that was selected.

Remaining Design Decision

Screw threads presented certain challenges, primarily that accidental crossthreading could cause operational failure and possible damage. A threaded design would also require additional mechanism in the Tip Garage to rotate the tips and screw them into place, whereas tapers would only need to be pressed. Additionally, screw threads could be loosened by the vibration generated by drawing. Locking tapers were an attractive solution because they are self centering and the action of pressing down, during swapping and during drawing, could serve to more firmly lock the tip in place. Based on this reasoning, it was decided to build a prototype of the mating parts of the taper design, to evaluate the feasibility of the self locking taper.

Taper Prototype

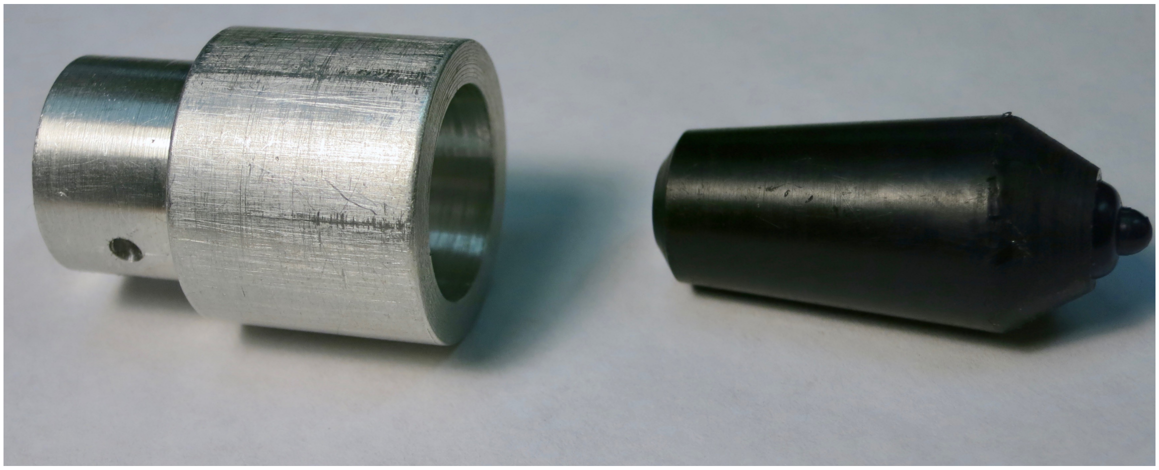
Tapers are commonly used in machine design to mate two parts when self-centering is desired. They rely on the friction between the two tapered surfaces to maintain contact, and so tapers are predominantly used when the two parts are subject to axial loading during use. Common uses include holding the cutting tools in CNC milling machines and both the live and dead centers on a wood lathe.

A prototype of the Stylus Shaft and the Tapered Tip was machined to assess the design. Particular care was taken to ensure that the angles of the taper of the two mating surfaces were as closely matched as possible to ensure good contact. The exact tolerance is difficult to calculate, but established machine-shop practices were followed to keep the taper within 0.1° of the nominal dimension. Tapers are generally considered to be "self locking" when the angle from the central axis is under 7°, making an included angle of under 14° [10] [7].

This means that once pressed together, they do not require additional mechanism to stay in place for light work, often drilling or other applications that do not involve side loads. As there were significant side loads in this application, a taper angle of 5° was used for this prototype.

The Tapered Tips were made from acetal homopolymer, an easily machined plastic that holds tight tolerances [1]. This plastic was used as the stylus material on the Beta 0 because its low coefficient of friction (0.2 static, 0.35 dynamic) results in reduced side loads when drawing, compared to aluminum (0.61 static, 0.47 dynamic) [2].

The diameter of the Stylus Shaft in the Beta 0 design (Figure 3.2) was too small to house the tapered coupling, so the diameter was increased from 12 mm to 20 mm. This size was chosen because the longest bushing that could be used without interfering with other printer components was 20 mm long. This length-to-diameter ratio of 1 for the shaft/bushing combination kept the design well within the accepted range of $\frac{1}{2}$ to 2 [9]. If the system were outside of this range, it would have been more likely to have had issues with binding. This prototype was made with these key dimensions in mind, seen in Figure 3.13.



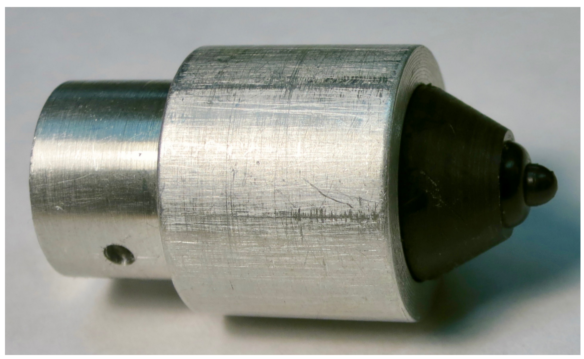


Figure 3.13: Prototype of the aluminum Stylus Shaft and the plastic Tapered Tip, separated in the top image, and assembled in the bottom. The Engagement Taper and the Clearance Taper are labeled for reference.

This prototype was more successful than anticipated. The taper seemed to hold firmly, even when only seated with light pressure, and there was no perceptible play between the parts when drawing by hand. After drawing with ∼3 lbs of downforce, the taper did not release when shaken, or when they were pulled with hand force. The parts did release easily when a light impact was administered to the back of the Tapered Tip through a hole in the aluminum piece. This suggested that an actuator of moderate size and strength could be used to release the taper in order to release a tip at the garage.

The encouraging results of this early prototype were the final factors that led to the decision to move into the detail design phase of a TCS that used *Replaceable, Tapered Tips*.

3.3 Detail Design of Tapered Tip System

At this point, the design had resolved into two subsystems, the *Drawing Assembly* and the *Tip Garage*. The former is the system that controls a Tapered Tip for swapping and applies various levels of downforce with it for drawing. The Tip Garage is the system that holds the unused Tapered Tips, and actuates them upward to engage with the Stylus Shaft and downward to avoid conflict with other printer systems when not in use.

3.3.1 Drawing Assembly

A SolidWorks® design of the Drawing Assembly can be seen in Figure 3.14. This design makes use of the same mechanism for controlling force as the Beta 0: a stepper motor (*Stylus Motor*) loading a helical spring to apply a desired downforce for drawing. The spring is not normally visible because it is enclosed in the Motor Arm and the Stylus Arm, but it can be seen in Figure 3.15, where two Arms are made partially transparent. As noted above, the diameter of the Stylus Shaft has been increased. In addition, the Spring Arm had to be modified to avoid conflicting geometry. Additionally, the Engagement Taper of the Tapered Tips needed to be made 0.25 in shorter than the prototype. This change was needed to ensure that the TCS would be able to move far enough to pick up a new Tapered Tip.

To eject the Tapered Tip, the Stylus Shaft was designed with a hole for the shaft of the Solenoid to fit through and contact a 45° bevel that was added to the top of the Tapered Tips, identified in Figure 3.15. Figure 3.16 shows this action. The Solenoid was secured in a 3D printed Solenoid Bracket which allowed for 2mm of longitudinal movement. This enabled adjustment of where in the throw of the Solenoid it contacted the Tapered Tip. The Solenoid was able to apply more force the closer this contact was to the most extended position of the Solenoid; see Appendix B for the force curve and other specifications of the solenoid.

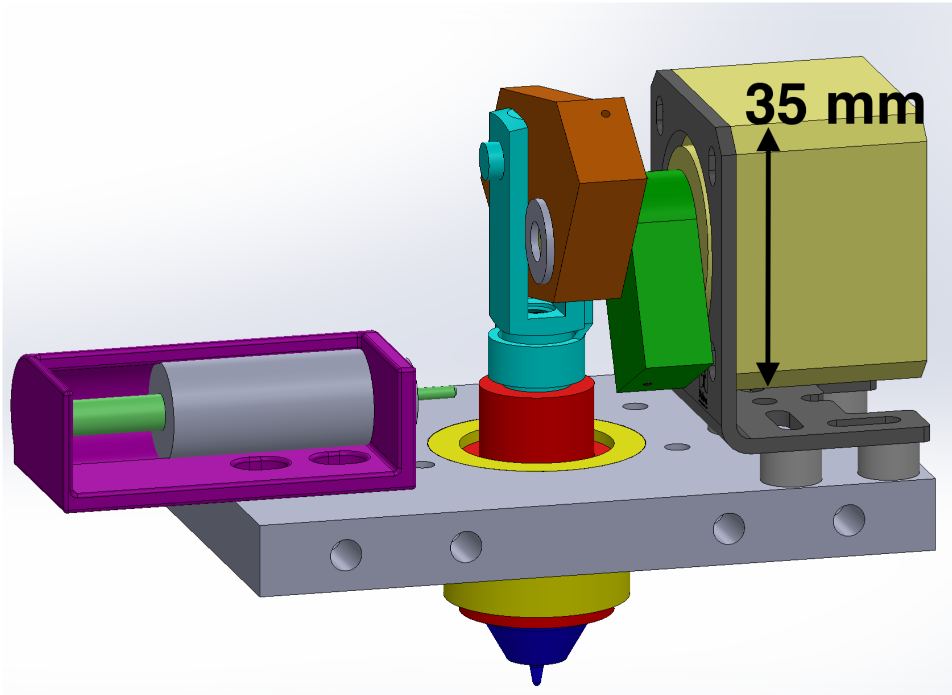


Figure 3.14: SolidWorks® model of the Drawing Assembly of the TCS with the Stylus Shaft in the down position. In this model, the Stylus Shaft is red and the Tapered Tip is dark blue. The Solenoid Bracket is magenta, the body of the Solenoid is grey, and its shaft is light green. A clevis connecting the Motor Arm to the Stylus Shaft is teal.

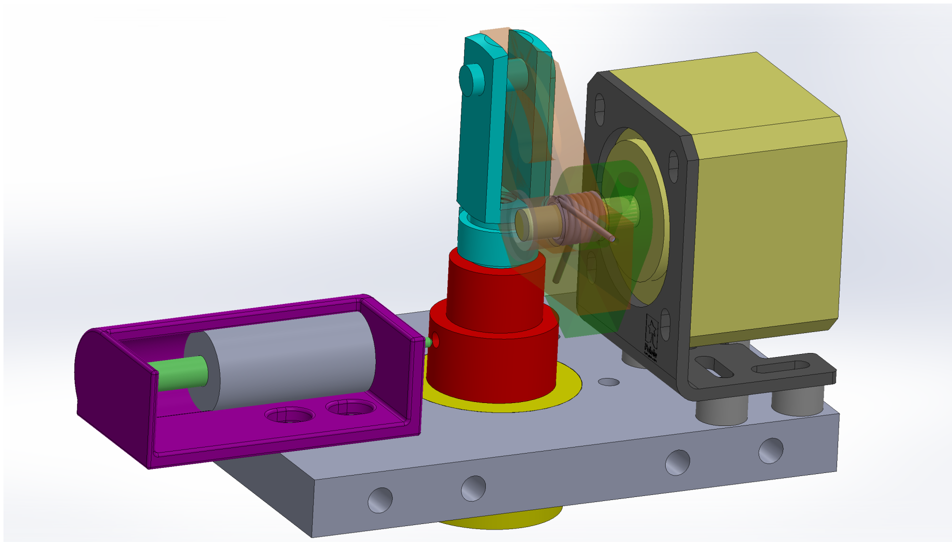


Figure 3.15: SolidWorks® model of the Drawing Assembly of the TCS with the Stylus Shaft in the up position. The Motor Arm and the Stylus Arm have been made partially transparent to show the helical spring (labeled). The hole in the Stylus Shaft for the Solenoid to release the Engagement Taper is also labeled.

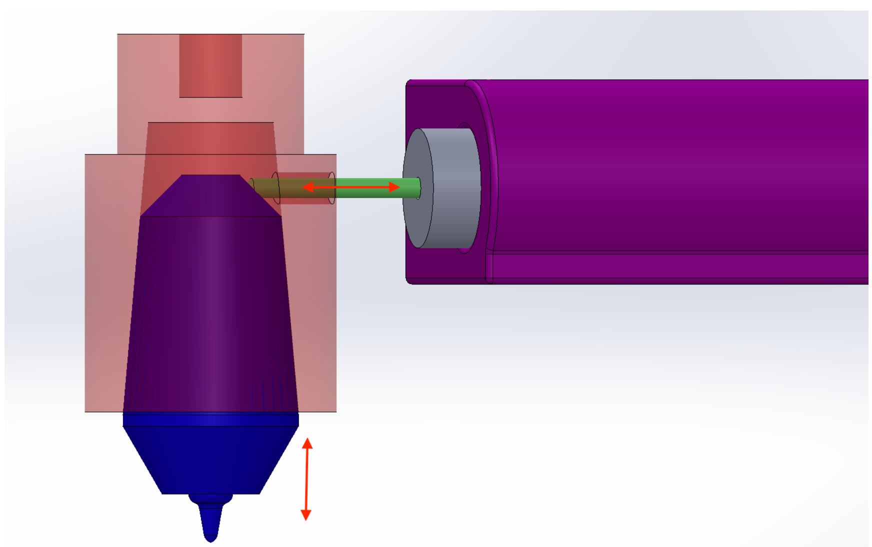


Figure 3.16: SolidWorks® model of the chamfered end of the shaft of the Solenoid (green) contacting the top of the Tapered Tip (blue) to release it from the Stylus Shaft (red, transparent).

3.3.2 Tip Garage

The Tip Garage, seen in Figure 3.17 serves two functions: it holds the Tapered Tips when not in use, and it moves them up and down when needed. This second function was necessary because the Drawing Assembly cannot produce sufficient negative-Z travel to engage and lift a Tapered Tip unless the "parked" Tip is moved up to meet it. This is explained in more detail in section 3.4.3.

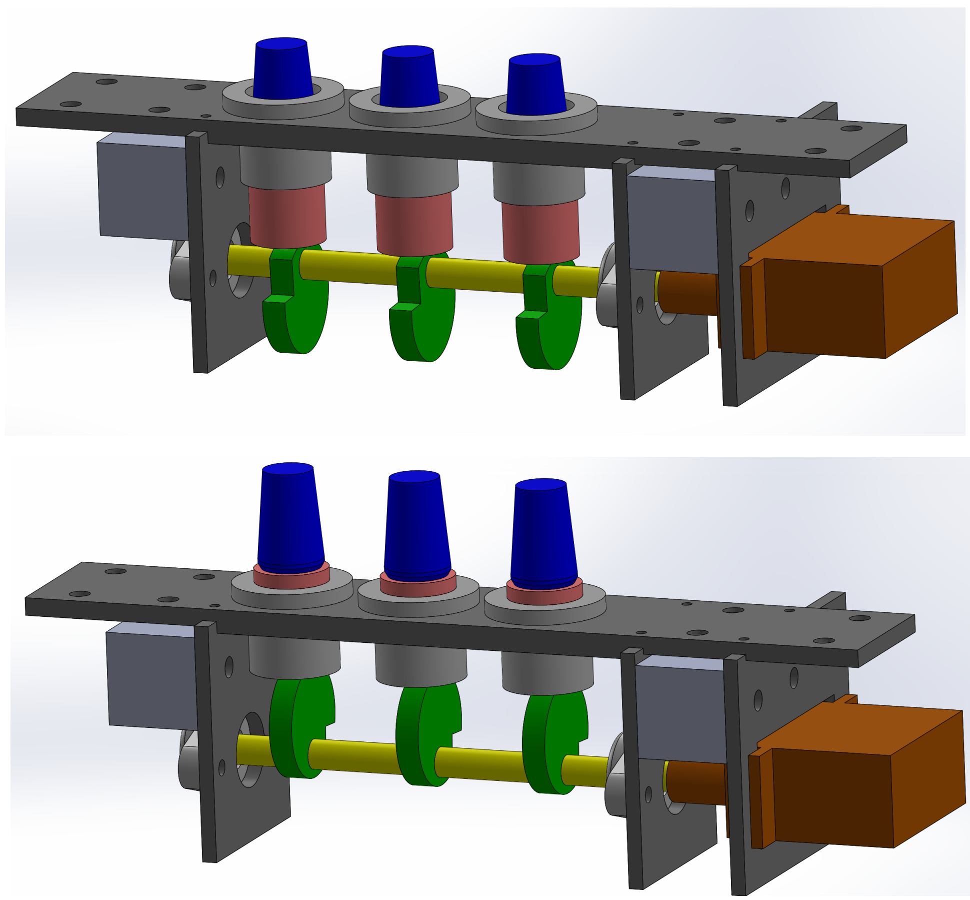


Figure 3.17: SolidWorks® models of the Tip Garage for the TCS. The top configuration shows the Tapered Tips in the lowest position, and the bottom configuration shows the Tips in their highest position, after being raised by the Cams. In these models the Garage Motor is orange, the Cams are green, the Cam Shaft is yellow, the Pistons are red, and the Tapered Tips are blue.

The design of the Tip Garage uses a servo motor (*Garage Motor*, see Appendix C for specifications) to rotate a series of *Cams* fixed to the *Cam Shaft*, which is supported by self aligning bushings. Each Cam raises up a Tapered Tip, cross section of this assembly seen in Figure 3.18. Each Tip rests on a *Piston* which slides through a bronze bushing. The vertical movement of the Tapered Tips is 0.5 in from the lowest point to the highest. The rationale for the features of this design includes the following reasoning:

1. It only requires one additional actuator to move all the Tips.
2. The Garage Motor used is capable of 240 oz·in of torque, over four times more than the Stylus Motor. This amount of torque is likely more than was needed, but it ensures that the cams would rise, regardless of startup friction.
3. At the raised position, any force involved in seating the taper is supported by the bearings holding the Cam Shaft, not resisted by the motor.
4. The motion is smooth, allowing the taper time to seat, unlike solenoids which would have involved some degree of impact.

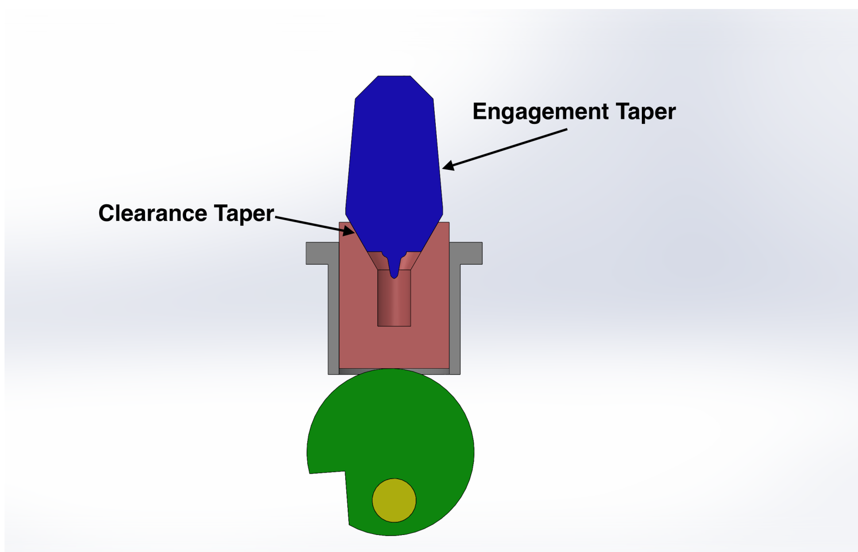


Figure 3.18: SolidWorks® model showing a cross-section of the Tip Garage. The Piston (red) holds the Tapered Tip (blue), and is actuated by the Cam (green), which is rotated by the Cam Shaft (yellow).

3.4 Build

3.4.1 Drawing Assembly

The fully built and installed Drawing Assembly can be seen in Figure 3.20. The Tapered Tips are turned on a metal lathe and the drawing tips are made using radius cutting tools sized $\frac{1}{32}$ to $\frac{1}{8}$in. These tools allow for the tips to be made with a hemispherical shape by cutting just to the central axis of the lathe. If the tool continues to cut beyond the central axis, it will make a more pointed conic section, as needed for the particular size and shape of each tip, see Figure 3.19. The Tapered Tips are made from acetal homopolymer, as in the prototype. These parts are all made with a tolerance of ± 0.001 in. The largest size drawing tip, called the *Ball* was $\sim \frac{3}{16}$ in, the *Standard* size tip was $\sim \frac{1}{8}$, and the *Sharp* drawing tip was $\sim \frac{1}{16}$, measured at the point where the conical section of the tip meets the round section, see Figure 3.19.

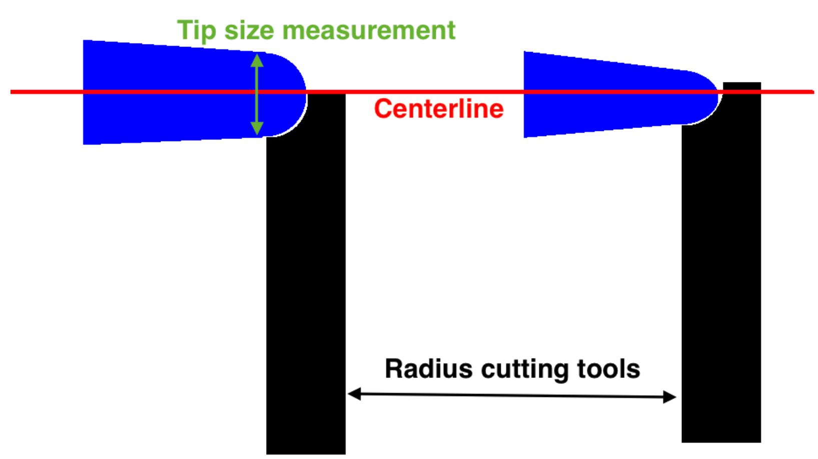


Figure 3.19: Cross section sketch of machining Tapered Tips. The left sketch shows the making of a hemispherical tip by cutting just to the centerline, and the right sketch shows the making of a tip with a more pointed conic section by cutting past the centerline. The location of measuring tip size is shown by the green arrow.

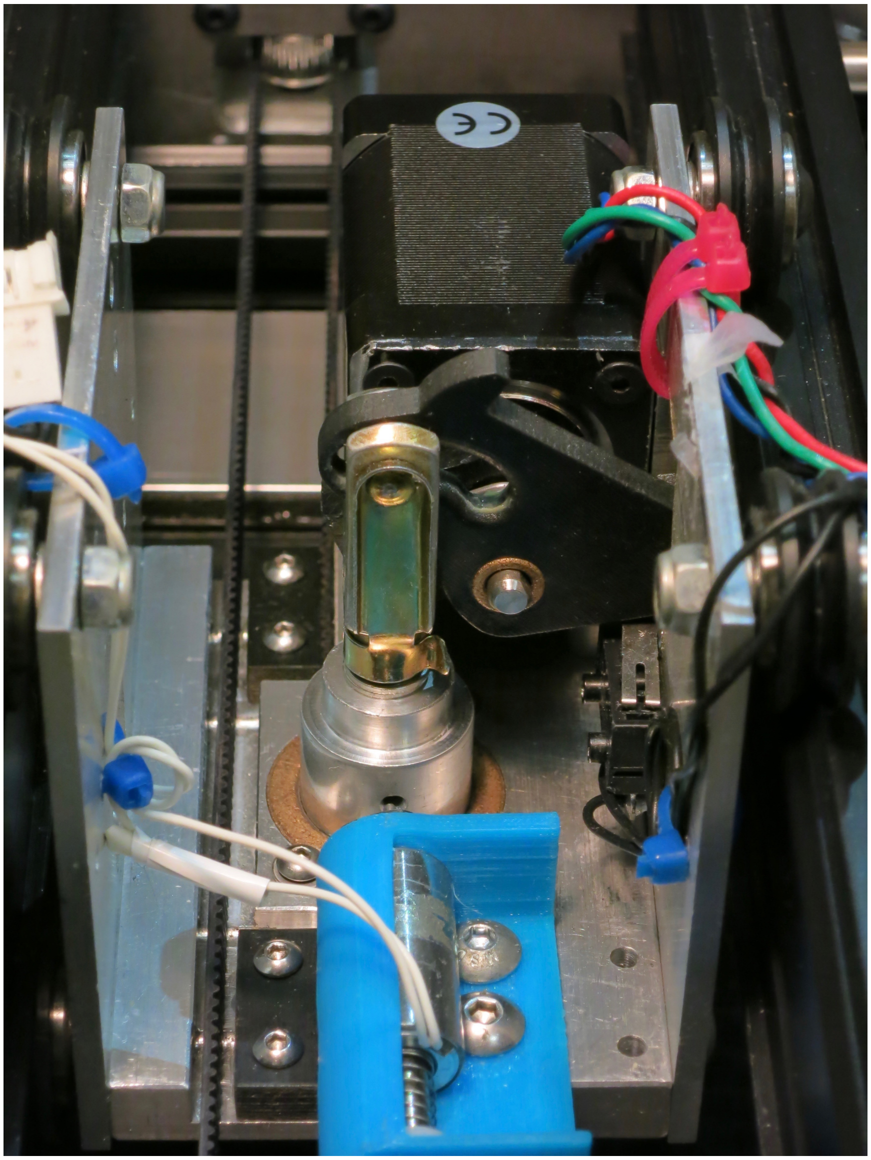


Figure 3.20: Drawing Assembly, built and installed in XY Transport System.

3.4.2 Tip Garage

The final, assembled Tip Garage is seen in Figure 3.21. This system did not require the same level of precision as the Drawing Assembly because it was not involved in scratch embossing. It only needed to be able to reliably lower the Tapered Tips and raise them with enough force to seat the Engagement Taper. In fact, a small amount of play in the Pistons will allow the Tips to self-center into the Stylus Shaft when engaging. As the precision of machining was unnecessary, time was saved by using a laser cutter to cut these parts from sheets of acetal homopolymer. This CNC machine uses a 60 Watt CO_2 laser to cut, and it is repeatable to within 0.0005 in. The way that the laser cut through material sometimes resulted in part edges that were a few degrees away from being perpendicular to the top surface. The design of the Tip Garage anticipated this, and so where a laser cut edge was mated to a flat surface, a piece of extruded aluminum was used as a gusset, ensuring that they would be perpendicular. Grooves and holes parallel to the top face could not be made on the laser cutter, so these features were cut on a milling machine after laser cutting was complete.

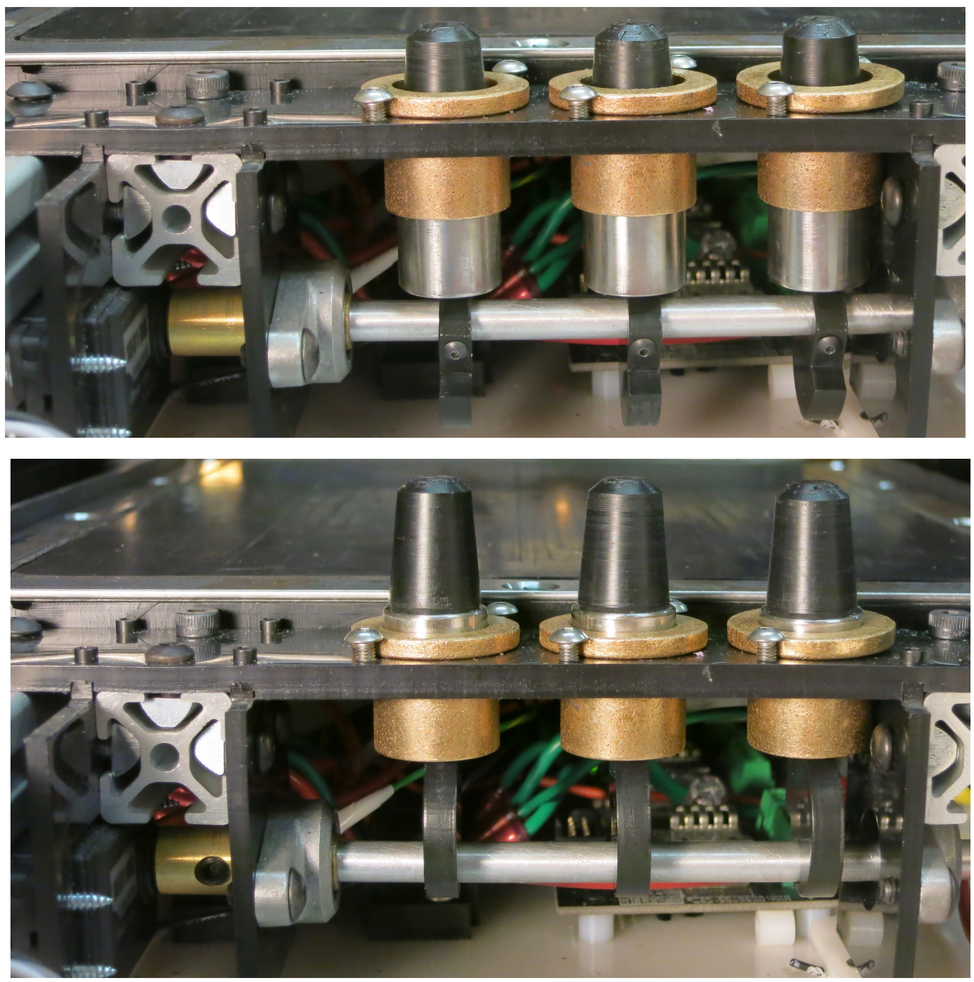


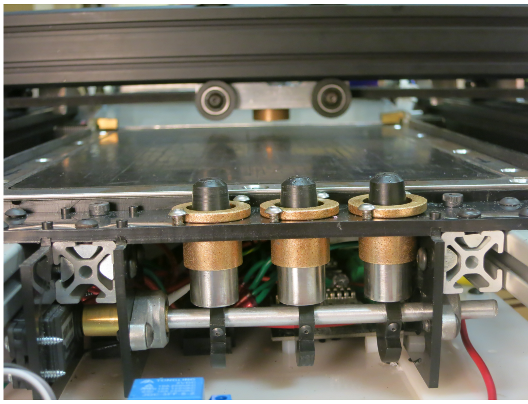
Figure 3.21: Assembled and installed Tip Garage for the TCS. The top picture shows the Tapered Tips in the lowest position, and the bottom picture shows them in their highest position, after being raised by the Cams.

Along with the flat plates that make up the frame of the Tip garage, the Cams were cut with the laser cutter, and they were secured to the Cam Shaft with size 2-56 steel screws, visible in Figure 3.21. The Pistons were turned on the lathe from 304 stainless steel because it is corrosion resistant and high-density. The density was important because gravity was the only force keeping the Pistons in contact with the Cams. Prototype Pistons were initially made from aluminum and it did not lower under their own weight. To ensure that they lower correctly, the Pistons were also made a .002 in smaller than their nominal dimension of .625 in, so that they had a slip-fit in their bushings. The self aligning bushings allow 5° of angular misalignment between the Cam Shaft and the Garage Motor. The mechanism for mounting the Garage Motor involves rubber mounting posts, and this addresses minor lateral misalignment between it and the Cam Shaft.

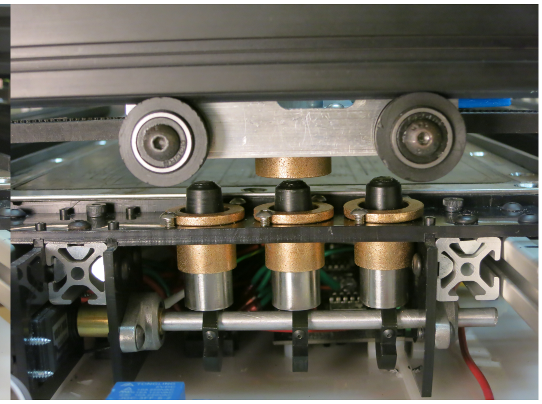
3.4.3 Operation

Picking up a new Tapered Tip, shown in Figure 3.22, required the following steps:

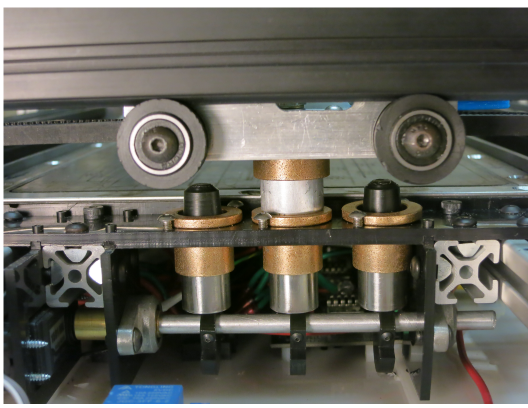
1. To avoid interfering with other printer components, the Stylus Motor raises the Stylus Shaft until it is fully inside its bushing, and the Tapered Tips are all moved to their lowest position.
2. The XY Transport System moves the Drawing Carriage until the Stylus Shaft is directly above the desired Tapered Tip.
3. The Downforce Assembly lowers the Stylus Shaft until it was pressed against the bushing of the Tip Garage with $\sim$ 0.2 lbs of force.
4. The Garage Motor rotates the Cam Shaft to raise the Tapered Tips and seat the Engagement Taper into the Stylus Shaft. This raises the Stylus Shaft by $\sim$ 0.25 in, which is resisted by the helical spring in the Downforce Assembly, generating the necessary jamming force to properly seat the Engagement Taper.
5. The Stylus Motor lifted up the Stylus Shaft and newly connected Tip fully into its bushing, ready for use.



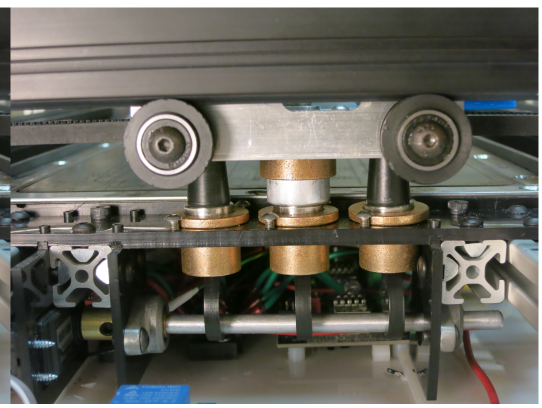
(a) Step 1



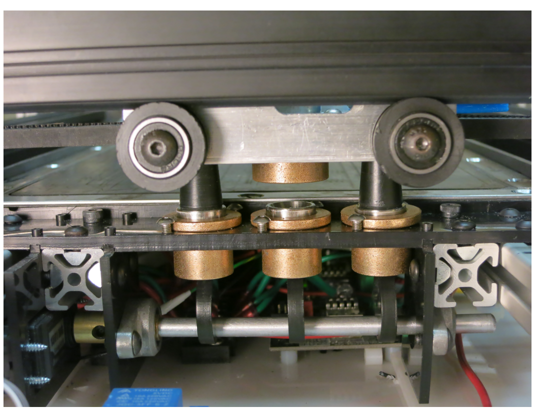
(b) Step 2



(c) Step 3



(d) Step 4



(e) Step 5

Figure 3.22: The process of picking up a Tapered Tip.

3.5 Evaluate

3.5.1 Constraint Evaluation

A series of constraints for the TCS were outlined in Section 2.2. This design successfully met each constraint, as described in the following list.

1. The first constraint was that all mechanical components were required to fit within the volume of the Beta 0 printer. This constraint was met, as the Drawing Assembly fits onto the Drawing Carriage without increasing its size, and the Tip Garage fits into an unused space of the Beta 0 printer frame.

2. The second constraint was that no changes were to be made to the Beta printer that fundamentally affected or hindered its operation. This constraint was met; much of the additional mechanism was entirely separated from other printer systems, and the only change to existing components was the widening of the Stylus Shaft. The Stylus Shaft in the TCS moves within the same type of precision bronze bushing as used in the Beta 0, and the increase in size of this component did not affect the performance of the printer in any noticeable way.

3. The third constraint was that the TCS could not increase the projected parts cost the printer by more than \$150. This was met, as the total material cost of the TCS was ∼\$80, and the most expensive component was the \$19.99 servo motor. This cost will come down when the TCS is manufactured, as materials and components are bought in larger quantities. See Appendix D for the full parts list, including prices.

4. The fourth constraint was that TCS can not increase the time required to print a sheet by more than 15 seconds per print. The time that the TCS adds to a print is based on the number of different Tips used. The TCS takes 4-6 seconds to exchange a tip, so if all three Tips are used, there will be two exchanges. This will add only 8-12 seconds to the print time, meeting this constraint.

5. The fifth and final constraint was that the TCS cannot noticeably increase the noise generated by the printer from its current level. This constraint was met, as the operation of the TCS generates significantly less noise than other printer operations, such as embossing Braille.

3.5.2 Reliability Testing

Once built and functioning, the TCS was tested for reliability. Excepting part breakage, there are two potential modes of failure for the TCS, and both were assessed. As this was a prototype system, requiring further work to become a consumer product, both of these tests are indicators of reliability but are not intended to get a statistically validated measure of failure rate, as that degree of testing is beyond the scope of this work.

Failure Mode 1: Unintended Taper Disengagement

The first potential failure mode for the TCS is the disengagement and dropping of the Tapered Tip from the Stylus Shaft, either during scratch embossing or other printer functions. The only way to assess the likelihood of this failure is to use the printer frequently and make note of any occurrences of this failure mode. At the time of writing, the Drawing Assembly of the TCS has been in use for over six months. During this time, an estimated 700 prints were made, both for the purposes of this project and by E.A.S.Y. in the normal course of their work. During this time, there were no occurrences of Tapered Tip disengagement. This suggests that this failure mode is very infrequent, and that the TCS can be considered reliable in this regard.

Failure Mode 2: Unsuccessfully Exchanges Tip

The potential failure mode of TCS is for the system to unsuccessfully exchange the Tapered Tip. This could happen if the Solenoid does not successfully release the previous Tapered Tip or if the next tip does not successfully seat in the Stylus Shaft. In a way, these are two different failure modes, but as they were tested in conjunction with each other, they are both discussed here. The Tip Garage was built and installed after the Drawing Assembly, and most of the graphics printed by E.A.S.Y. do not involve the exchanging of a tip. Thus, there have been far fewer tests of this failure mode. To determine the likelihood of the TCS unsuccessfully exchanging a tip, it was tested by exchanging tips 100 times, continually rotating through the three tips. During this test, the TCS successfully ejected the current tip and picked up the new one with zero failures. This suggests that this second failure mode is unlikely, and that the TCS can be considered to have some measure of reliability for successfully exchanging tips.

3.5.3 Tip Strength Analysis

Setup

The component of the TCS that is most likely to break TCS is the sharpest Tapered Tip, because it has the smallest cross sectional area. No breakage was observed during use, so this tip was analyzed in finite element analysis software to determine the safety factor involved. This analysis also gives insight into the amount of deflection that the tip experiences during drawing.

The following analysis was done in SolidWorks® 2017 Simulation software. A fixed boundary condition was applied to the tapered section of the tip to simulate the support provided by the Stylus Shaft. The force was applied to the drawing end perpendicular to the long axis of the tip, shown in Figure 3.23. The peak value of force was measured at 16.8 N by pulling the carriage with a force gauge while drawing with the sharpest tip. The peak force value was also found when pulling the carriage without drawing, 10.26 N. This value is a measure of the sum of frictional and inertial forces of the carriage, which would not be transferred to the tip. Thus, it was assumed that the force on the Tapered Tip is 6.54 N; equal to the force to pull the carriage while drawing minus the force required to pull it without drawing.

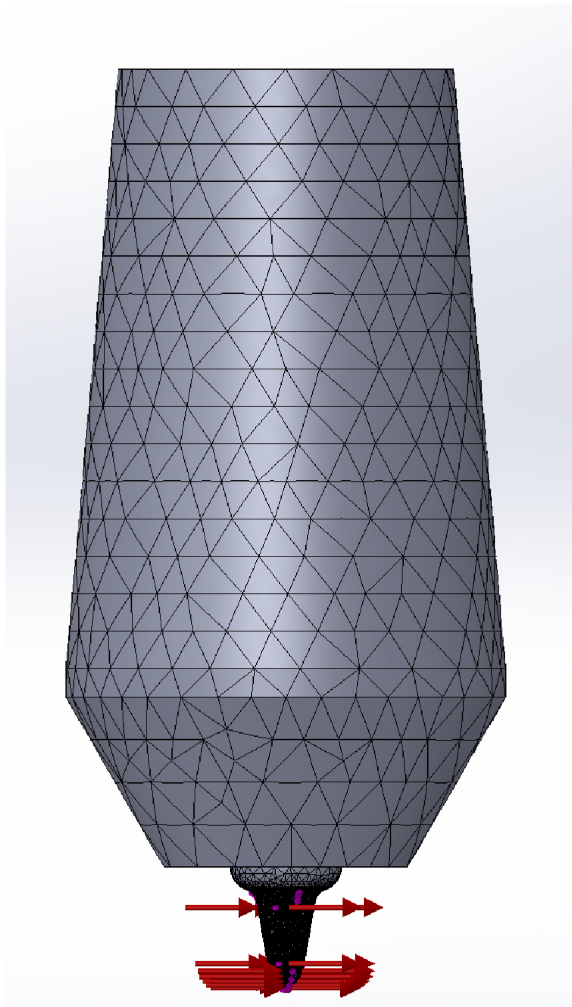


Figure 3.23: SolidWorks® simulation of drawing force on the smallest Tapered Tip. The red arrows show the direction of the force, and the location it was applied to.

The mesh for this analysis uses 279686 elements for the solution to be independent of mesh size. At this level of refinement, more than doubling the number of elements only changes the solution by 0.0544%. This mesh was much more refined at the tip than it was for the body of the part, as seen in Figure 3.24.

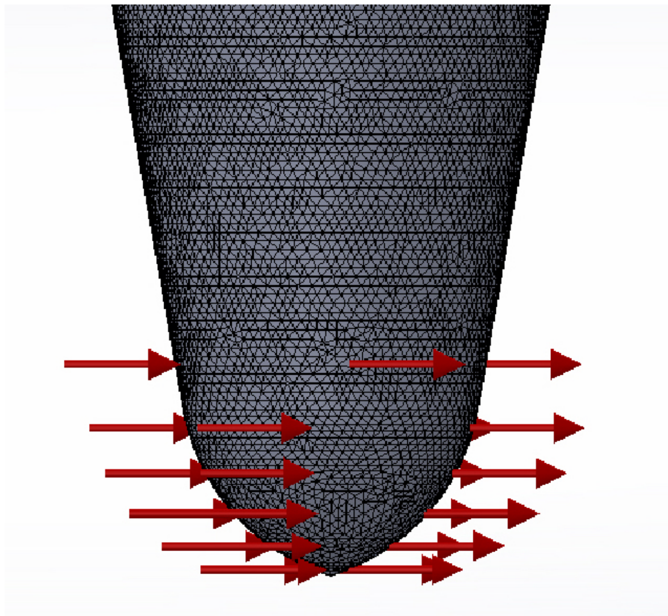


Figure 3.24: Close-up of mesh refinement at tip.

Results

The plot of the Von Mises stresses from this analysis is seen in Figure 3.25 and Figure 3.26. This analysis shows that there are two small stress concentrations on the tip, one in compression and one in tension, as the tip was undergoing similar deflection to beam bending. These stress concentrations are localized at the surface of the part, as seen in a cross section of the stress plot: Figure 3.26.

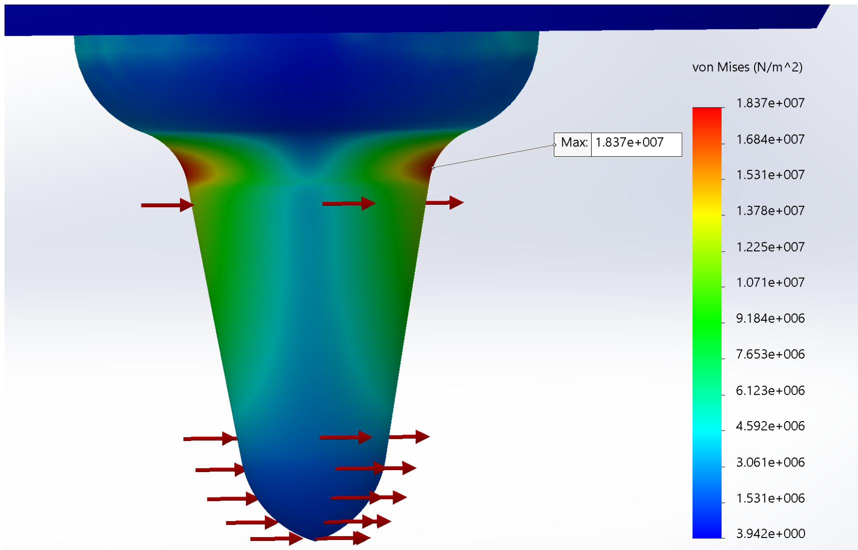


Figure 3.25: Simulated Von Mises stresses on the tip

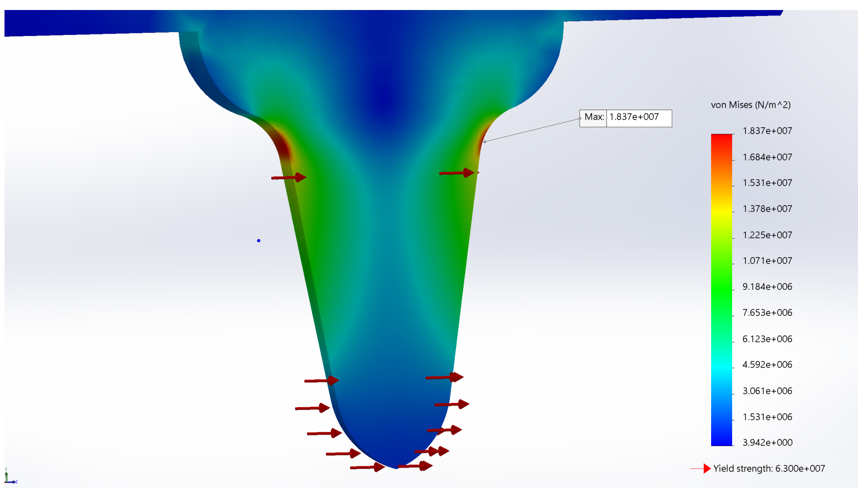


Figure 3.26: Cross section of simulated Von Mises stresses on the tip.

The maximum Von Mises stress seen in this analysis was 18.37 MPa, with a corresponding strain of .00527. As the yield stress of the acetal homopolymer that the tip is made from is 63 MPa [1], the safety factor for this stress analysis is 3.4. Additionally, this stress is significantly below the endurance limit for this plastic. Per the manufacturer's data sheet, the stress on the tip would need to be 30 MPa for it to fail after 10,000,000 cycles, see Appendix E. As the stress found in this analysis is less than half that, fatigue should not be an issue for this part for the lifetime of the printer. The tip also experiences very minor deflection. The maximum found was 0.0321 mm, seen in Figure 3.27.

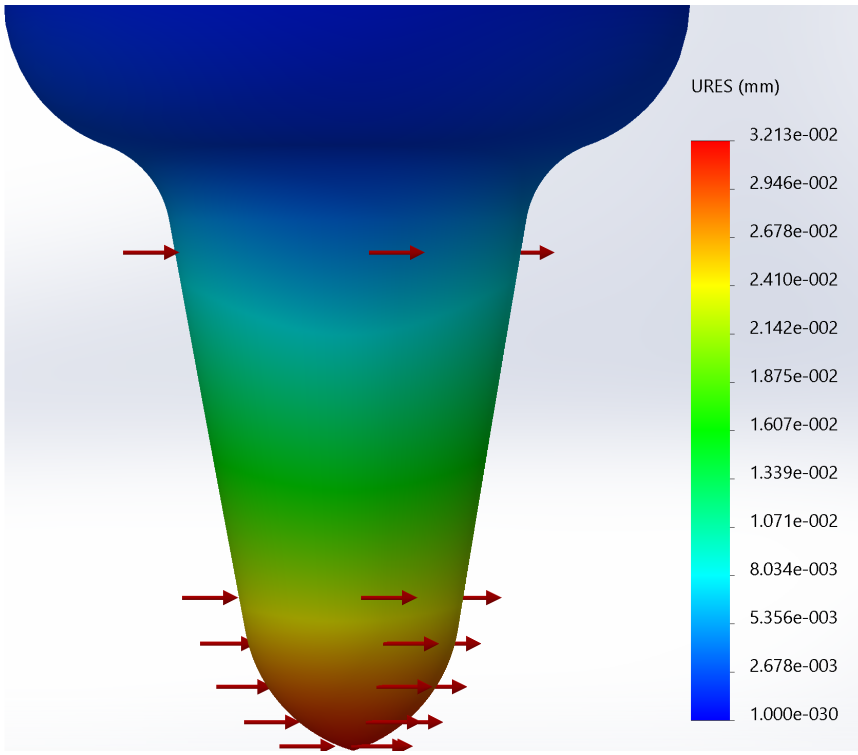


Figure 3.27: Simulated displacement of the tip.

Conclusions

The analysis showed that the smallest Tapered Tip is in no danger of breakage during drawing. The maximum stress is well below the yield stress, and low enough that fatigue is not a concern. Furthermore, the deflection of the tip is negligible, at 1.2 percent of the width of the narrowest scratch embossed lines. These results suggest that no design changes need to be made to the Tapered Tip for the purposes of rigidity or durability.

Chapter 4

Texture Design and Evaluation

4.1 Selection of Textures

4.1.1 Observations

To design the textures that the TCS would produce, a series of ad hoc experiments were performed, making textures (patterns of lines and divots) by hand with a variety of patterns, stylus tips, and levels of downforce. The purpose of these tests was to identify the *Texture Set* based on how Distinct they were, as determined by the perceptions of the author. Distinctness, the first criterion for Usefulness, was chosen because it was assumed that the more successfully the textures met this criterion, the more likely they were to fulfill the other two criteria. The Texture Set was not intended to be an exhaustive, optimized, or commercialization-ready set of all Useful textures; rather it was a set of six textures selected in an attempt to demonstrate that the TCS *can* make Useful textures. In commercial application, entirely new textures may be designed, as needed by TVIs and informed by their experience. Our reasoning was that if the Texture Set was found useful through user evaluation, our demonstration of the Usefulness of the TCS would be confirmed. If not, further tests with other textures would be required to investigate more thoroughly the patterns and printer settings, if any, that predict success. The following observations came from these tests:

1. Textures made with the same stylus felt increasingly similar to one another as line spacing decreased below 0.5 in apart, or less. With lines more closely spaced, the objective pattern had very little impact on the subjective feel of the texture. For example, a grid of vertical and horizontal lines spaced 0.5 in apart was nearly impossible (for the author) to distinguish from the same grid rotated 45°. This is consistent with past work done at E.A.S.Y. which suggested that

scratch embossed lines must be more than 0.5 in apart for a graphic to be clear (minimum standard spacing is 0.375 in for read-only tactile graphics [8]). It was believed that this was due to the inherently periodic nature of the scratch embossed lines. Since most BVI users perceive the inherent "bumpiness" of the lines, when the concentration of lines approaches the spacing of the bumps within a line, the objective (intended) pattern of lines will become unclear.

2. Textures based on a pattern of shapes (e.g. a checkerboard) spaced slightly under the size of the user's fingertip (0.5 in for the author) were found to be very Distinct from the more densely packed textures. Similarly, the different line patterns (e.g. parallel vs. hatched) also seemed to be more readily perceptible when the spacing was 0.5 in or more.

3. For the more "dense" texture patterns, the overall feel predominantly came from the feeling of the lines themselves, which was determined primarily by the tip size and the downforce used. For example, two samples of the 0.5 in grid of lines could be made perceptibly Distinct from one another by using different styluses to draw each sample.

4. Textures that included some features made with the Sharp tip and some made with the Ball tip were not as unique as expected. The sharp features were largely responsible for the overall feel of the texture, and the softer features from the Ball tip faded in comparison and so contributed little.

5. Textures made with the Ball tip exhibited a slightly different scratch embossing phenomenon. The buckling that occurs in the line seemed to produce less rigid "bumps", so that touching the line would cause the location of the buckling pattern to shift longitudinally. This resulted in textures made with this tip having a uniquely "soft" feeling. It was likely this phenomenon that caused the subjects in the Preliminary Psychophysical Experiment reported in Section 2.4 to report that textures made with the APH Ball felt categorically different from the rest.

4.1.2 Texture Set

From these observations, it was determined that the Texture Set would have six textures, two from each tip, one *sparse* (lines spaced more than 0.5 in apart) and one *dense* (lines spaced 0.5 in apart or less). The Texture Set can be seen in Figure 4.1. The following is a description of each texture:

1. This sparse texture was scratch embossed with the Ball tip. It is made up of 0.5 in circles arranged in a grid.

2. This dense texture was made with the Ball tip, and the lines were spaced 0.25 in apart. The long lines of this pattern enhanced the low-rigidity buckling phenomenon that was observed in lines made with this stylus, and this gave this texture a unique feel.

3. This sparse texture was made with the Standard tip by pressing dots down into the TDS without XY translation. These dimples slightly raised the area of the TDS around the circumference of the dimple, producing a circularly symmetrical crater-like contour that dominated tactile perception. This texture could be Varied in Degree by spacing the dots by 0.25, 0.375, or 0.5 in.

4. The dense texture for the Standard tip was made from 0.5 in squares. The squares were made by scratch embossing a series of overlapping lines to deform the whole area of each square, i.e. produce a shape all of which is in positive relief.

5. The sparse texture for the Sharp tip was made from 0.25 in long lines, spaced 0.25 in apart. These lines were sufficiently short that scratch embossing did not occur in the usual way. Instead, each short stylus stroke produced a single raised parabolic feature, 0.125 in long. This texture can be Varied in Degree by scribing it with all three styluses.

6. The dense texture for the Sharp tip was a grid of lines, spaced 0.25 in apart.This texture was able to be Varied by Degree by using the other two styluses to make it.

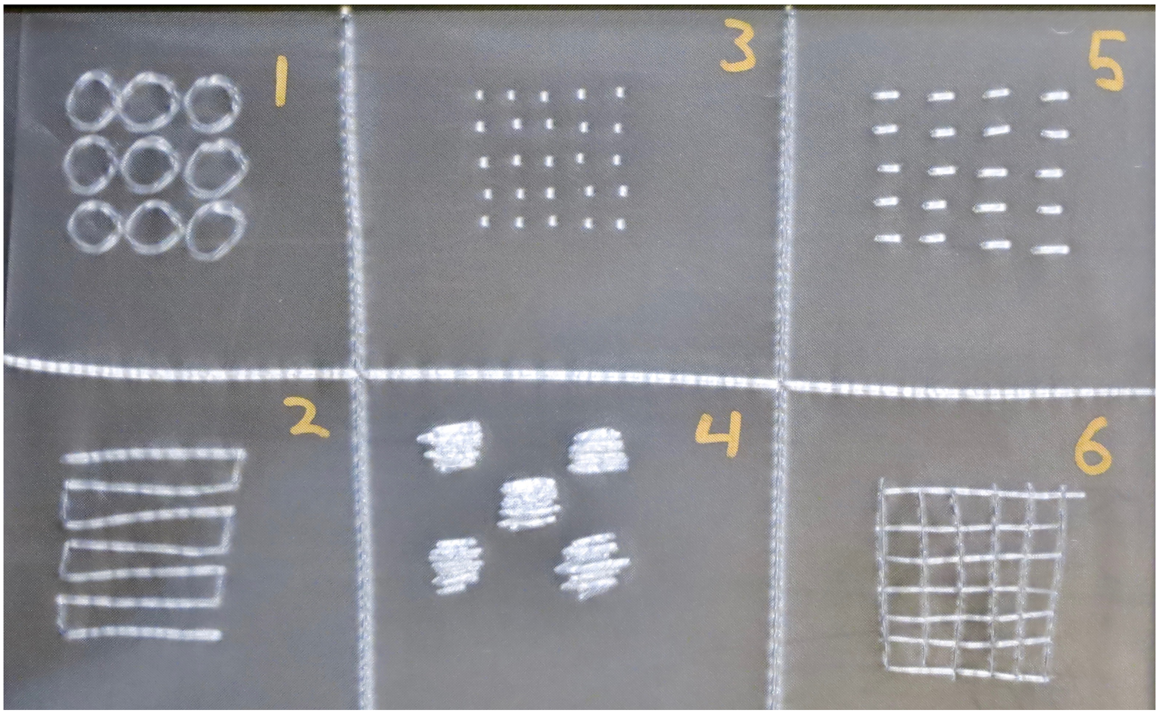


Figure 4.1: The six textures of the Texture Set, scratch embossed by hand. These textures are described above.

4.1.3 Creation of Textures Using the TCS

There is a degree of finesse involved in hand drawing that needed to be accounted for when converting these 6 hand drawn textures to be made by the TCS. The TCS makes use of open-loop control of down force; there is no sensor to detect incipient tearing of the TDS. Tearing is also more likely because the TCS holds the stylus vertically, while hand drawing was nearly always done with the stylus tilted in the direction of drawing. These differences made tears in the TDS common for the more "aggressive" textures, such as #4 and #6 (see above). This was addressed by slowing the speed of drawing from 3 inches-per-second to 2.

Another complicating factor was that the Standard tip used for printing with the Beta 0 printer was required to be slightly smaller than the "standard" stylus used to make the textures by hand. As previously discussed, the size for the Standard tip was required to be the size that the Beta 0 printer to make lines that are not a part of textures. Thus, the Standard tip and the Sharp tip produced lines that were more similar than desired. To address this, the Standard tip was used with less downforce to make its textures less similar to textures made with the Sharp tip, when making the different degrees of textures #5 and #6.

4.2 Psychophysical Texture Evaluation

4.2.1 Background

The purpose of this experiment was to evaluate the success of the textures made by the TCS, in terms of how well they meet the Usefulness criteria, as previously discussed. Each *Test* (see Figure 4.2 below) used a *Test Set*, a series of TDS with textures scratch embossed on them using the TCS. The order and layout for each sheet in the Test Set can be found in Appendix F. The six subjects in this experiment were all BVI individuals living in Vermont, chosen based on their availability for this study. No demographic information was recorded in the spirit of Exemption 2, seen in Appendix G. The experiment was administered by Stephanie Bissonette TVI and COMS, Supervisor of Children Services at the Vermont Association for the Blind and Visually Impaired (VABVI). There were three Tests in this experiment, one for each Usefulness criterion: Distinctness, Recognizability, and Variability in Degree. This experiment was intended to evaluate the Usefulness of the textures, not the tactile abilities of the subjects.

4.2.2 General Methods

We define a Test as a set of Trials, conducted with each subject individually. Tests 1, 2 and 3 were intended to evaluate how well the Texture Set meets criteria for Usefulness 1, 2 and 3, respectively. Prior to each Test with each subject, the TVI provided them with a *Qualification Sheet*. The Qualification sheet provided an exemplar of the tasks they would be asked to do in the Test, but instead of textures made on the TDS, these sheets were composed of patches of different materials: fleece, sandpaper, felt, bubble-wrap, burlap, and the hook half of a hook-and-loop strap. The Qualification Sheets were designed to present an easier version of the task than those that comprise the Test. These Qualification Sheets had two purposes: to ensure that the subject understood the instructions for the test, and to establish that they met at least a minimum level of tactile ability.

The assumption was made that if a subject did not have the tactile ability to successfully respond to the Qualification Sheets (e.g. tell the difference between sandpaper and fleece) then they were not likely to represent the population of BVI subjects for whom the Texture Set was intended. If they gave correct answers for the Qualification Sheets, the subjects were given time to practice on five Practice Sheets with textures made by the TCS. The subject was given the option to go through the five

Practice Sheets a second time if they did not feel comfortable after one pass. This was done in part to attempt to reduce the effect of differences in prior tactile experience among the subjects. The length of time allowed for practice was limited by the approximate one-hour frame for this experiment, which was limited by subject availability and the TVI's time.

After Qualification and Practice, the Test began and the TVI recorded subject responses on an answer sheet prepared for this purpose. Each subject used the same Test Set, and the TVI followed a prepared script (see Appendix H for the full script) throughout to provide a degree of uniformity of protocol across subjects. Additionally, subjects with partial sight wore sleep shades to occlude their vision. Subjects were instructed that if they were unsure of an answer, they should not guess, and that they skip on that Trial with an opportunity to come back to it later.

Figure 4.2 shows a summary of the protocol, listing the number of Qualification Sheets, total trials, trials per subject, and number of textures involved for each Test. Each subject completed 57 trials, a number based on subjects' time availability, and the expectation that each trial would require less than one minute.

	Test 1	Test 2	Test 3
Qualification Sheets	2	2	1
Total Trials	126	108	108
Trials per Subject	21	18	18
Textures Tested	6	6	3
Trials per Texture	21	18	36

Figure 4.2: Summary of number and distribution of Trials in each Test.

4.2.3 Test 1: Evaluation of Distinctness

Methods

Test 1 was an evaluation of the Distinctness of the Texture Set. For this test, the TVI put a TDS with two textures on it in front of the subject. An example Test Sheet is seen in Figure 4.3. They were given a forced choice between two responses: *same* or *different*. Prior to testing, each subject was given two Qualification Sheets (QS). QS 1.1 included a sample of fleece and a sample of burlap, and QS 1.2 had two samples of fleece, seen in Figures 4.4 and 4.5. These Qualification Sheets were designed to prime the subjects to understand the amount of difference to expect; that an answer of different should mean that the two textures have more than just slight inconsistencies. This was done to attempt to prevent subjects from providing false different responses because of incidental variance among samples of a texture produced with identical TCS parameter values.

Figure 4.3: Example of a trial from Test 1. Texture #2 is being compared to texture #4.

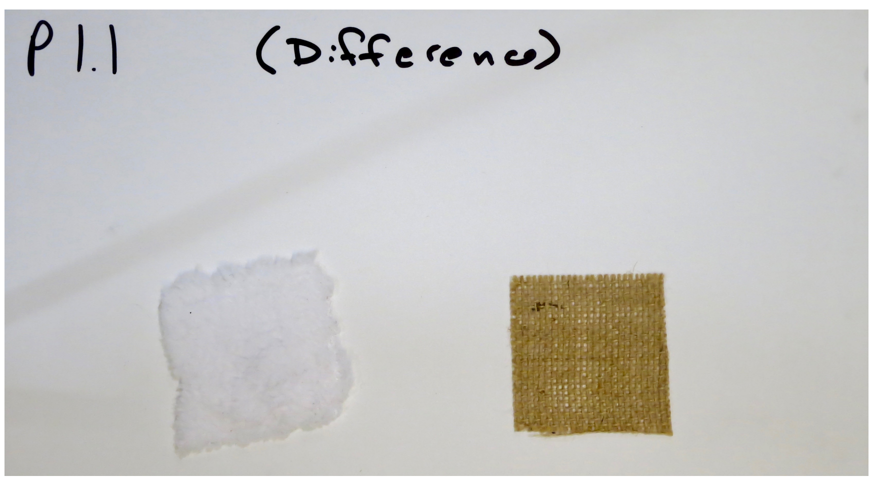


Figure 4.4: Qualification Sheet 1.1, made with a sample of fleece (left) and a sample of burlap cloth (right), both 2x2 in squares.

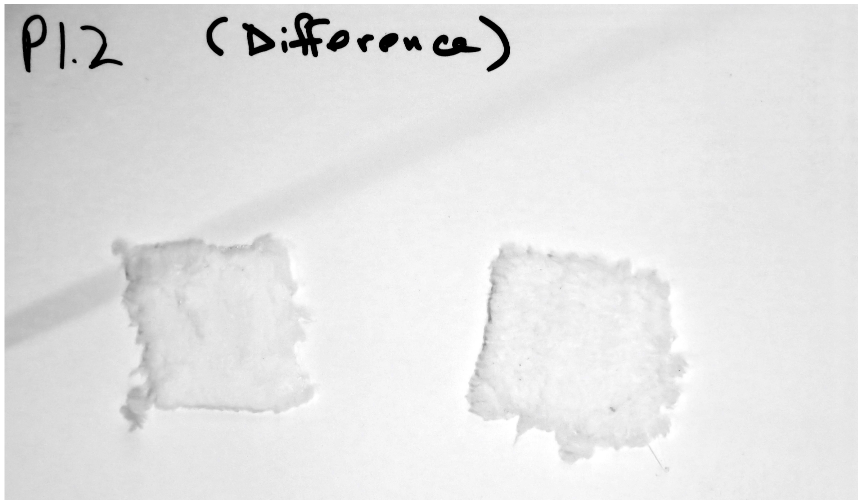


Figure 4.5: Qualification Sheet 1.2, made with two samples of fleece, both 2x2 in squares.

Following the Qualification Sheets, the subject was allowed to practice with pairs of textures printed on TDS to become familiar with the feel of the textures they would be encountering in the Test. After practicing, the Test began, with the TVI recording the responses. The Test Trials included every texture paired with itself, and with each other texture, in a randomized order. Due to a mistake in the preparation of the Test Set for this Test, texture #5 was not tested against itself, and instead it was tested against texture #6 twice. Thus, there were 21 trials; 5 where the correct answer was that the textures were the same, and 16 where the correct answer was that the textures were different.

Results

All six subjects successfully answered the two Qualification Sheets and so they all participated in this Test. The results from Test 1 are shown in Figures 4.6 and 4.7. In Figure 4.6, each bar represents the fraction of trials, for a particular texture and all subjects, in which the subjects responded correctly. Figure 4.7 presents the same data, organized by subject. All six textures generated correct responses in at least 75 percent of trials, and all subjects answered correctly in more than 75 percent of trials, with a mean of 86 percent and a standard deviation (SD) of 6.7 percent across the subjects, 7.7 percent across textures.

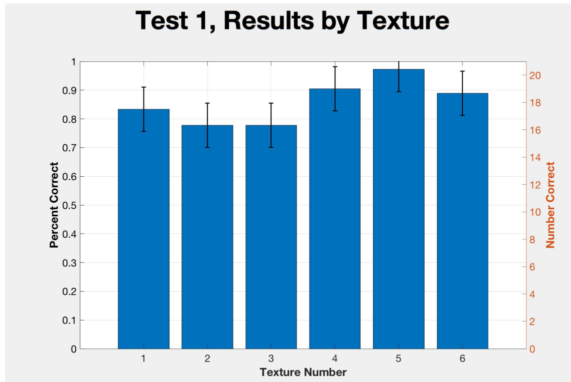


Figure 4.6: Results of first test, percent correct by texture #. Mean across textures = 86%, SD = 7.7%. The error bars in this, and other Figures represent one SD.

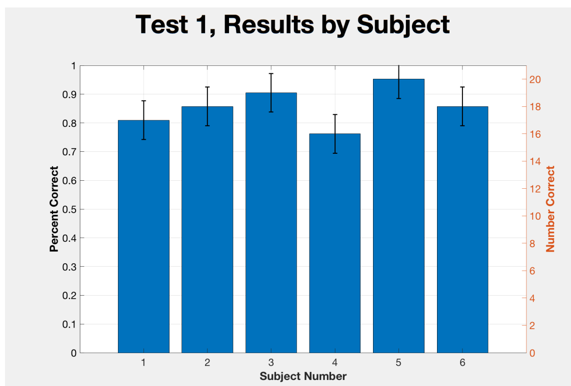


Figure 4.7: Results of first test, percent correct shown for each subject. Mean across subjects = 86%, SD = 6.7%

These results were also evaluated in two subsets, the Same subset and the Different subset, based on whether the two textures were made with the same line pattern and TCS parameters or not, shown in Figure 4.8. In the Same subset, textures #1, #2, and #6 were correctly reported as Same by all 6 subjects, compared to 4 of 6 subjects for #3 and 3 of 6 subjects for #4. (Texture #5 was not compared to itself due to the error noted above in the Test Set preparation.) In the Different subset, the textures were found Distinct more consistently. Every texture was correctly answered in at least 70 percent of trials, and some as high as 97 percent (#4 and #5).

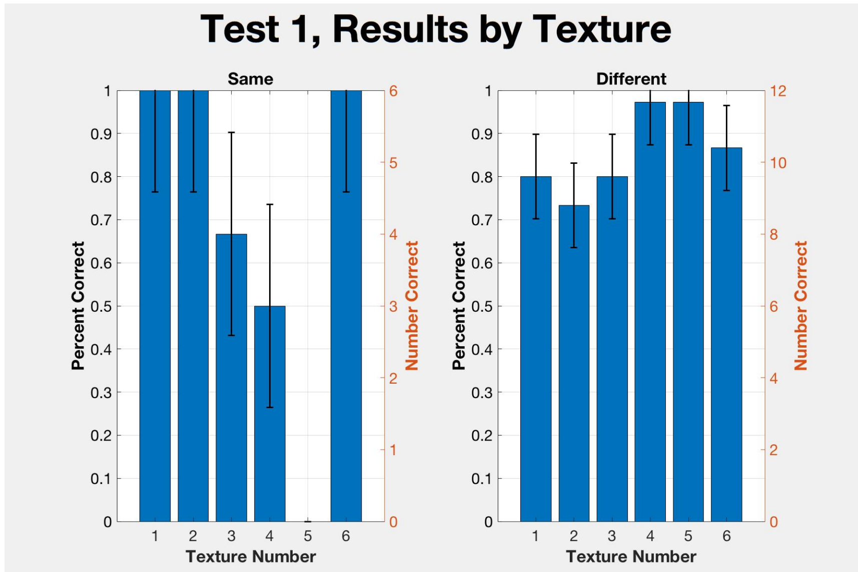


Figure 4.8: Results of Test 1, percent correct by texture #, separated into the Same subset (mean = 83%, SD = 23.6%) and the Different subset (mean = 86%, SD = 9.8%).

Discussion

The difference between the results for the Same and Different subsets may have been due to the Same subset having a much smaller number of trials per texture than the Different subset, 6 vs 30, dictated by the practical limitations of the size of the experiment. Thus, findings from the Same subset cannot be treated as suggesting a generalized conclusion. The results of Test 2 provide further indication as to how consistently two prints of a single texture can be identified as the same.

Assuming for the sake of discussion that the difference in results between the two subsets would hold for a statistically significant sample size, this finding would indicate that the success rate was higher when the two textures were different because that is an easier determination to make. This could indicate that subjects, knowing that there *are* objectively different textures are more likely to correctly provide a positive response (correctly identifying relatively large intended differences between two textures) than to correctly give a negative response (no difference between two textures). This seems likely since there is unavoidable variance among samples of the same texture because of the inherent variability associated with scratch embossing. By analogy, it should be fairly easy for a typically-sighted person to identify that a red square is different from a blue one, but it should be more difficult for them to determine if two blue squares are exactly the same shade of blue.

4.2.4 Test 2: Evaluation of Recognizability

Methods

Test 2 was meant to test how well the Texture Set met the second criterion for Usefulness: Recognizability. The printed TDS for this test presented the subjects with a *Reference Texture* at the top-right corner of the TDS, and five *Comparison Textures* (always five, whether or not one is a match to the Reference), seen in Figure 4.9. The subjects were asked to find the "match" for the Reference Texture among the Comparison Textures, or to answer that there was "no match" on the sheet. The five Comparison Textures were randomly ordered on the sheet, and the location of the match, if present, was also randomized. Just as in the Test 1, subjects were first given time with the two Qualifying Sheets, seen in Figure 4.10 and 4.11. QS 2.1 included a match for the Reference Texture, and QS 2.2 did not. This order was chosen to prime the subjects to have an understanding of how similar two textures need to feel in order to be considered a match.

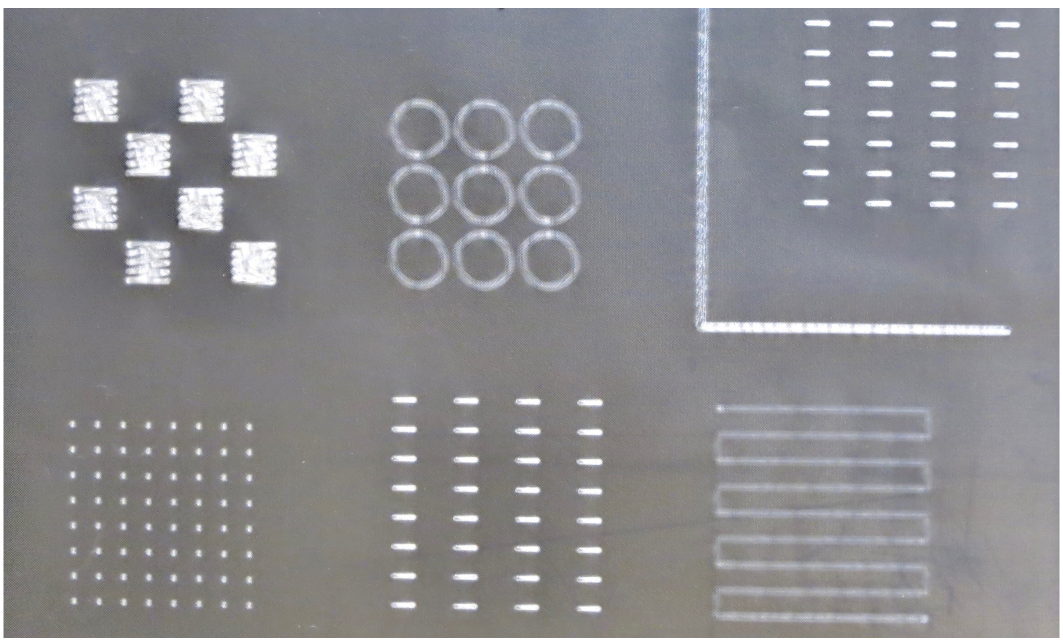


Figure 4.9: Example of a trial from Test 2, where Texture #5 is the Reference Texture, and the match is in the middle of the bottom row (location D)

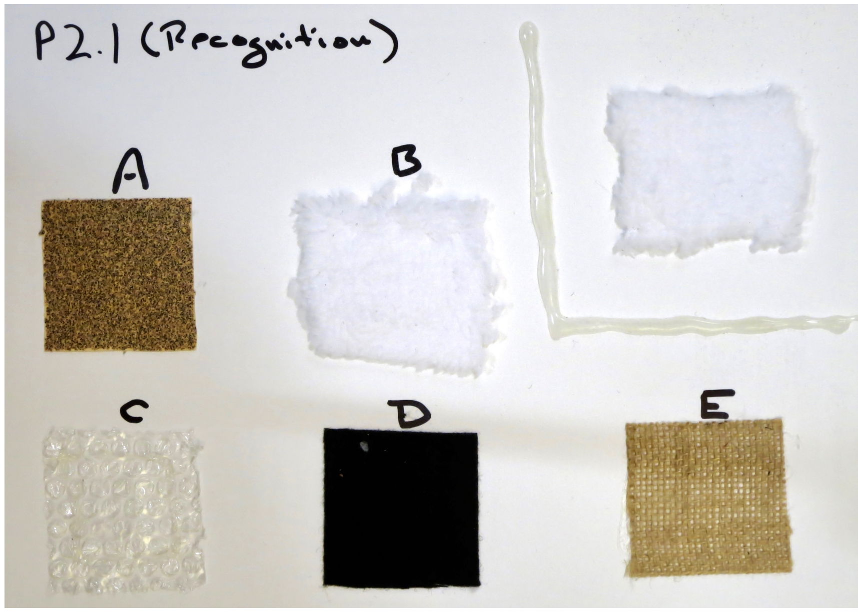


Figure 4.10: Qualification Sheet 2.1, where the Reference Texture is fleece, and the match is in location B.

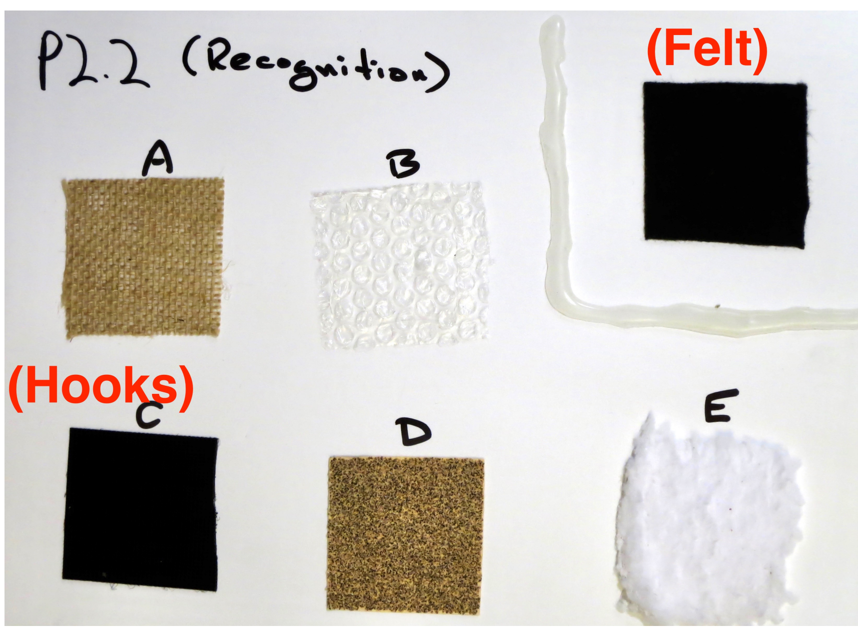


Figure 4.11: Qualification Sheet 2.2, where the Reference Texture is felt, and there is no match on the sheet (the dark sample in position C looks similar in the image, but it is sampled from the hook half of a hook-and-loop strap).

After successfully responding to the Qualifying Sheets, subjects were given time with the Test 2 Practice Sheets (textures embossed on a TDS) before the test began. Sheets that do *not* include a match (the Match Not Present subset) included all six textures from the Texture Set, one as the Reference Texture and the other five as Comparison Textures. The sheets that *do* include a match (the Match Present subset) only present five of six textures from the Texture Set since one of the five Comparison Textures matches the Reference Texture. Testing each texture against all six possible sets of non-matching Comparison Textures would have resulted in the Match Present subset including 36 trials, too many for the time constraints on the experiment. Instead just two trials for the Match Present subset were prepared for each Comparison Texture; so, for each Reference Texture there were two textures that were not on the sheet (one per trial). To make this Test more difficult, these two textures were selected as those considered the least least likely to be mistaken for the Reference Texture. In this way, the textures that were included in the Comparison Textures were those that were most similar to the Reference Texture, and therefore most likely to be incorrectly selected as the match.

This test consisted of 18 trials for each subject, 12 making up the Match Present subset (where one of the five Comparison Textures was a match to the Reference Texture) and 6 trials in the Match Not Present subset (where the Reference Texture was not repeated in the Comparison Textures).

Results

All six subjects successfully answered the two Qualification Sheets and participated in this Test. The pooled results for this test can be seen in Figures 4.13 and 4.12, organized by Reference Texture and by subject, respectively. On average, the subjects answered correctly in 73 percent of trials (SD = 15 percent). Textures #1, #2 and #3 (56-61 percent) were not answered correctly as consistently as textures #4, #5, and #6 (83-89 percent).

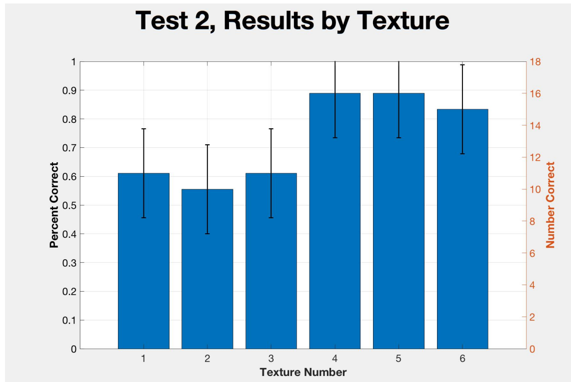


Figure 4.12: Results of Test 2, percent correct by texture #. Mean = 73%, SD = 15.5%.

Figure 4.13: Results of Test 2, percent correct shown for each subject. Mean = 73%, SD = 13.8%.

The data were separated into the Match Present subset (36 trials in total) and the Match Not Present subset (72 trials in total) in Figure 4.14. In the Match Not Present subset, when texture #1, #2, or #3 was the Reference Texture, subjects correctly answered that there was no match on the sheet much less consistently (33, 16, and 33 percent of trials, respectively) compared to when texture #4, #5, or #6 was the Reference Texture (83, 83, and 67 percent respectively). The results from the Match Present subset showed the textures generating more correct answers; all six were correctly matched in at least 75 percent of trials. Just as in the Match Not Present subset, textures #1, #2, and #3 were less successful (all three 75 percent correct) than textures #4, #5, and #6 (all three 91.7 percent correct).

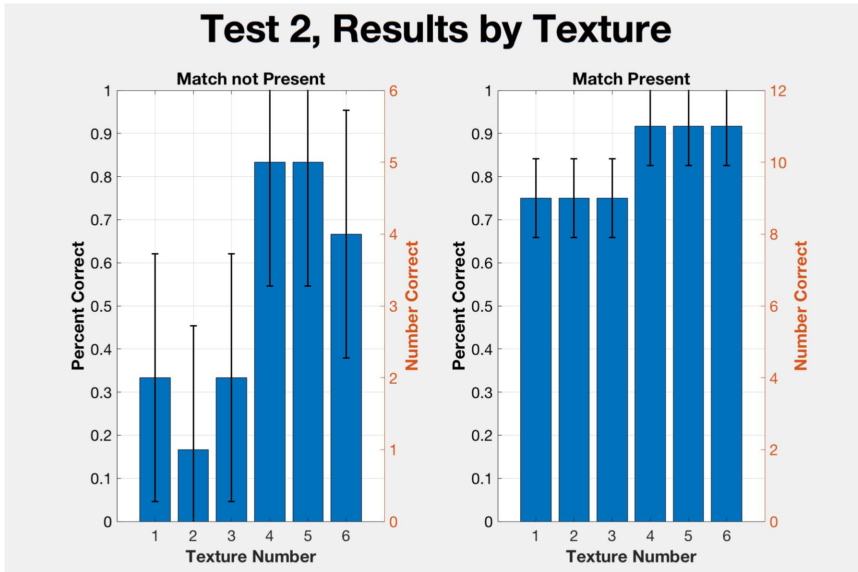


Figure 4.14: Results of Test 2, percent correct by texture # and broken into the Match Not Present subset (mean =53%, SD = 28.7%) and the Match Present subset (mean =83%, SD = 9.1%).

Discussion

These results suggest that textures #1, #2, and #3 were less recognizable than the other three. These three textures performed worse than textures #4, #5 and #6 in both subsets of results. Interestingly, these lower performing textures were all made with what was defined above (Section 4.1.1) as "soft" features. Textures #1 and #2 were made with the Ball tip, resulting in scratch embossed lines with a wider and more rounded cross section than textures made with the other tips, and texture #3 was made from divots pressed below the surface of the TDS. This may suggest that the feel of textures made with softer features was less dependent on the spatial pattern, and more dependent on the feel of the individual features. If this is true, textures with different patterns, but similar-feeling features should be mistaken for one another relatively often. To investigate if this was the case, the data presented in Figure 4.15 compares the Reference Texture to the texture chosen as the match for all incorrect answers from this test. These data were available because the TVI recorded the subjects' responses, not whether they answered the question correctly or not. This shows that 72.4 percent (22 out of 29) of all incorrect answers given during this test were from trials where the Reference Texture was #1, #2, or #3, and the chosen answer was #1, #2, or #3. This suggests that textures #1, #2, and #3 were frequently confused for one another.

Incorrect Answers						
	Reference Texture					
Reported:	**1**	**2**	**3**	**4**	**5**	**6**
No Match	1	0	0	0	0	1
1		6	3	0	0	0
2	5		4	1	0	0
3	1	2		0	1	1
4	0	0	0		1	0
5	0	0	0	0		1
6	0	0	0	1	0	

Figure 4.15: Incorrect answers for Test 2, comparing the Reference Texture to the answer reported. The cell at row 1, column 2, for example, indicates that when texture #2 was the Reference Texture, texture #1 was incorrectly reported as the match six times.

The difference in results between the two subsets (Match Present and Match Not Present) suggest that, just as in Test 1, when looking for a match, it is easier to identify a positive result (a match) than it is to correctly identify a negative result (that there is no match present). This was an encouraging finding, in the sense that the Match Present subset was a better representation of how tactile graphics are used. Consultation with TVIs who use tactile graphics has indicated that when textures are used for Recognizability, such as in tactile maps, a match is *always* present because the textures included in the legend always have one or more matches in sections of the map.

4.2.5 Test 3: Evaluation of Variability in Degree

Methods

Each Sheet from the Test Set 3 consisted of three samples, in a horizontal row, of a single texture from the Texture Set, as shown in Figure 4.16. The three samples were printed in an attempt to differ from each other only in "degree" of some prominent subjective feature. Subjects were asked to rank the three textures from *least* to *most*. The subjective feature on which they based their ranking was intentionally left undefined. Since the range of meaning of a graded texture (e.g. map legends) is virtually unlimited, it was important not to bias or limit subjects by imposing terminology such as "more or less dense" or "lighter/darker."

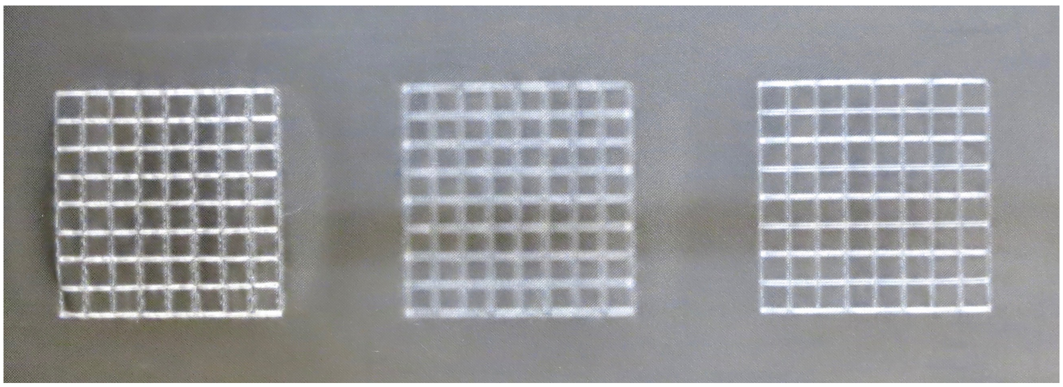


Figure 4.16: Example of a trial from Test 3, where Texture #6 is made with each of the three different size Tips. The correct order for these three textures from least to most is middle, right, left.

Textures #3, #5, and #6 were used for this test. To produce textures that subjects would perceive as varying only by degree, printing parameters were varied systematically. For Textures #5, and #6, all three tip sizes were used, keeping the patterns and all other printing variables (excluding down force) constant. The expected correct answers for these two textures was that the texture made with the Ball tip was the "least," followed by the texture made with the Standard tip, and the Sharp tip made the texture that was the "most." Texture #3 was varied by changing only the spacing between the divots where least was the divots spaced furthest apart, and most was the divots spaced closest together. What constitutes a correct response in this Test is more complicated than the previous two Tests, as it is possible that for some or all of these textures, the subjects will order the three samples of texture consistently across Test Set, but not in the order that was expected. This possibility will be discussed further in the Section 4.2.5 below

The Qualification Sheet for this test included three samples of sandpaper, 60, 150, and 320 grit, seen in Figure 4.17. Just as in Tests 1 and 2, subjects that successfully answered the Qualification Sheet were given time to practice on textures made on the TDS before the test began. The Test Set included all 6 possible orders for each of the three variations of the textures: 6 trials per texture and 18 trials total for each subject in this test. The order of the Test Set was randomized, and the same for each subject.

Figure 4.17: Qualification Sheet 3.1, including samples of three different grits of sandpaper. The order of the samples from least to most is: left, right, middle.

Results

All six subjects successfully answered the Qualification Sheet and so they all participated in this Test. The results from Test 3 are seen in Figures 4.18 and 4.19. As for Test 1 and Test2 , these graphs represent the complete pool of 108 trials organized by Texture and by subject. Textures #5 and #6 were successfully put in (the anticipated) order in 86.1 percent and 91.7 percent of trials, respectively, while texture #3 was only correctly ordered 33.3 percent of the time. This Test had the highest n value of 36 trials per texture, and the SD across these three textures was the highest seen in the results so far, 32.2 percent. This was due to only three textures being tested instead of all six, and the large variance in number of correct answers generated by texture #3 relative to textures #5 and #6. The SD for the correct answers given by the different subjects was much lower, 9.7 percent, and the mean was 70 percent. This suggests that the subjects performed similarly to one another, making most of their errors with just one of the three Textures.

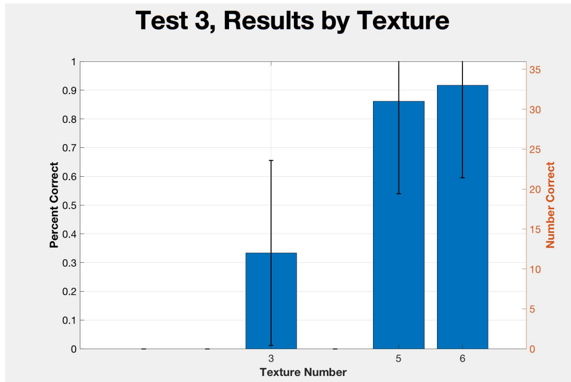


Figure 4.18: Results of Test 3, percent correct by texture #. Mean = 70%, SD = 32.2%.

Figure 4.19: Results of Test 3, percent correct shown for each subject. Mean = 70.4%, SD = 9.7%.

Discussion

These results clearly indicate that texture #3 was much less successful with regard to its Variability in Degree, compared to textures #5 and #6. This Test was more complicated than Test 1 and Test 2, in the sense that the subject was required to provide three answers in each trial (least, middle, most). Also, an unknown variable for this test was if the subjects would agree on what least and most meant. The low SD across the subjects' responses indicates that they agreed on what these terms meant. The low percentage of correct responses for texture #3 does not contradict this, as the reverse-of-expected order was given in only 22 percent of trials. This suggests that these subjects did not have a different understanding of least and most, rather that they were not able to reliably tell the difference between the three degrees of texture #3.

4.2.6 Summary of Usefulness Evaluation

Due to the practical limits of an MS project and the difficulty of accessing BVI subjects in Vermont, only six subjects were recruited. Thus, all of the data recorded from this experiment is descriptive, and statistical significance was not an expectation. This experiment was undertaken as one element of the standard paradigm for a design project, to provide measures of how well an alpha prototype meets the Design Objectives for a limited user sample. For this project, that generic mandate translates to providing insight into how well the prototype Texture Set meets each of the three criteria for Usefulness: Distinctness, Recognizability, and Variability in Degree.

Usefulness is not a binary measure, and there is no clear threshold of correct answers above which a texture is considered Useful. This is further complicated by considering the many factors associated with BVI students' educational success and, more specifically, their varying degrees of familiarity with tactile graphics. Thus, our expectation has been that the Texture Set (and other textures) produced by the TCS would be Useful for some substantial fraction of the BVI population. By analogy, the NFB estimates that only 12 percent of blind school-aged children are able to read Braille, yet Braille continues to be produced, sold and promoted as an essential tool for BVI education.

This work was pursued in part to design a system that would eventually be included by E.A.S.Y. LLC in a commercial interactive tactile graphics printer. In that product development context, the question of, "how Useful is Useful enough?" is part of a multi-factor business decision. A decision to include the TCS as a printer feature will be based on the incremental production cost of the TCS and all the determinants of the additional market that it would allow the company to access. This decision will depend further on whether printers will be marketed to be used to print tactile graphics content at educational sites, or used at a central publishing site to do mass production of hard copy for sale. These determinations are beyond the scope of this Masters project. Based on this reasoning, the summary below will not set a threshold to assert definitive claims about the Texture Set as being Useful or not Useful; rather, it will assess how well the Texture Set met each criterion for our subject group.

In all three Tests, subjects answered the questions correctly across a majority of the textures. In the tests for Distinctness and Recognizability, all textures generated correct answers at in least 75 percent of trials that mimicked real-world applications. In the test to assess if textures can Vary in Degree, the two successful textures generated correct answers in nearly 90 percent of trials. The "sharper" textures (#4, #5, and #6) performed consistently better across the three tests. Textures #1, #2, and #3 performed well in the first two tests, but texture #3 was unsuccessful at Varying by Degree. Additionally, these three textures also were often mistaken for each other in the second test, suggesting that to improve effectiveness, only one of these three textures should be used on a particular page. In conclusion, these results suggest that most (not all) of the textures tested were very successful at these three tests, and the Texture Set was found to be Useful in a large fraction of cases.

Chapter 5

Conclusions

The purpose of this design project was to expand the capacity of printing technology that produces interactive raised-line graphics by creating a system to print textures that meet specific criteria for Usefulness. Students who are blind or have low-vision (BVI) do not have the same access to graphical curricular content as their sighted peers. This significantly affects their education, particularly in STEM subjects. Introduction of interactive tactile graphics is one of the only ways for BVI students to access graphical content, and is uniquely suited to teaching drawing skills. Furthermore, the addition of textures to tactile graphics is essential for the graphics to be unambiguous and to communicate information about spaces and regions.

The system developed in this project for printing tactile textures was designed as an enhancement of an existing beta prototype printer for interactive tactile graphics, co-developed at UVM and E.A.S.Y. LLC. Various methods were considered for expanding the range of lines and marks, and therefore textures, that the printer could create. In a preliminary experiment, two design directions were considered: increasing the temperature of the drawing tip, or varying its size. Heating the stylus tip affects scratch embossing because the TDS are made from a thermoplastic, so their mechanical properties are greatly affected when heated to or above the glass transition temperature of ∼180 °F. The effects of scratch embossing with a heated tip were relatively unknown. In contrast, the authors had significant experience showing that changing the size of the drawing tip dramatically changes the physical properties of the scratch embossed lines.

An experiment was performed to compare textures made with various tip sizes and temperatures. The results demonstrated that varying the size of the drawing stylus tip would afford the greatest range of printed textures. Based on this finding, the Texture Creation System (TCS) was designed with this new functionality.

Various methods of changing the size of the drawing tip were discussed and evaluated for feasibility, according to standard engineering design practice. Two design categories were found to be feasible and promising, Selectable Tip designs and Replaceable Tip designs. By definition, the Selectable Tip designs use a Stylus Selector to translate or rotate a desired tip into place for drawing. The Replaceable Tip designs use interchangeable tips that attach using screw threads or a self-locking taper, and are deposited in a Tip Garage when not in use. These concepts were subjected to further consideration and a Pugh analysis comparing their predicted ability to offer various Desirable Attributes. Based on the outcome, the Replaceable Tips design using self-locking tapers was chosen to proceed to the detail design stage.

The TCS was fabricated, integrated with the beta printer, and evaluated. The self-locking Tapered Tip mechanism was in use without an occurrence of failure over six months of use, printing over 700 graphics. The mechanism for tip release and replacement at the Tip Garage was tested through 100 cycles without failure.

Because of its relatively small size and resultant higher stresses during scratch embossing, the Sharp drawing tip was assumed to be the most likely part to break, so it was analyzed using finite element analysis software. The part was found to be in no danger of failure under loads in excess of nominal. The safety factor for the Von Mises stress was calculated at 3.4. Additionally, this analysis demonstrated that the Sharp tip will not be in danger of failing from fatigue, even after 10 million loading cycles.

The TCS design successfully addressed all of its defined constraints:

- Physical Compatibility: All components of the TCS fit well within the footprint and printing carriage of the Beta 0 printer; they do not hinder the sheet feed, Brailling, sheet clamping or scratch embossing functionality of the printer in any way.

- Speed: Changing the Tip takes 4-6 seconds, adding at most 12 seconds to a print if it involves the use of all three tips (two exchanges). This is under the constraint (set by E.A.S.Y. LLC partners) that the TCS could not add more than 15 seconds to the time to print a page.

- Cost: The parts and materials cost for the TCS was $\sim$ \$80, significantly less than the maximum cost constraint of \$150 (also set by E.A.S.Y. LLC).

- Noise: The TCS does not increase the noise of the printer; the tip replacement process (releasing one tip and seating another at the Garage) is subjectively quieter than any other printer operation.

Following the design, prototyping and evaluation of the mechanical systems, a set of six example tactile textures (the Texture Set) was developed to represent and test the capabilities of the TCS. The Texture Set does not permit full measure of the textures that the TCS is capable of producing; rather, it was designed to permit a demonstration that the TCS can make textures that are found Useful. An experiment was designed and performed in which six BVI subjects made use of the textures according to a protocol that allowed assessment of their Distinctness, Recognizability, and Variability in Degree. The results from this experiment showed that in all tasks that mimic real-world use, the Texture Set was successful in at least 75 percent of trials.

Further work will be required to make the TCS ready to be an element of a commercial printer. While the TCS did not experience a failure during the testing it underwent during this project, it is likely that it will eventually fail to pick up or return a Tapered Tip during more extended operation. When this happens, a failed print, and possible damage to the TCS and other printer systems could result. Thus, design upgrades must include the addition of sensors to confirm that the Tapered Tips have been successfully exchanged before scratch embossing of a TDS continues.

Another way to improve the mechanical system of the TCS would be to machine the Tapered Tips on a CNC lathe, instead of with fixed-radius lathe tools. This could provide greater precision and repeatability to the geometry of drawing tips.

The final suggested improvement to the mechanical system is modification of the Downforce Assembly to enable it to draw with higher forces. This may improve the quality of the textures made with the Ball tip, and it would allow for even larger tips to be incorporated. At the maximum downforce of the current beta printer, larger tips than the Ball will not deform the TDS enough to successfully scratch emboss lines.

For the system to be ready for commercial use, there will also need to be a software package that can be called to apply textures to specified areas of a graphic digital file.

Future, larger-scale user testing should focus on a more extensive evaluation of the Texture Set, and other textures, to obtain statistically significant results regarding their Usefulness. Further study could also provide insight into what objective properties of the textures elicit certain subjective responses, i.e. *why* certain textures meet design criteria better than others.

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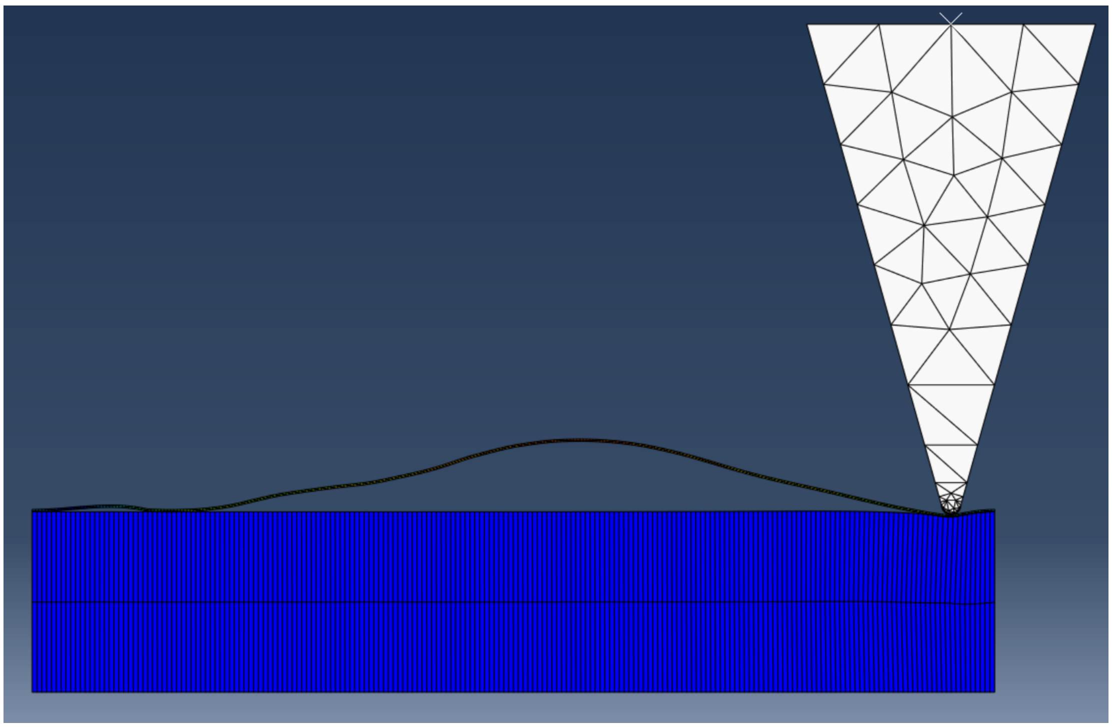
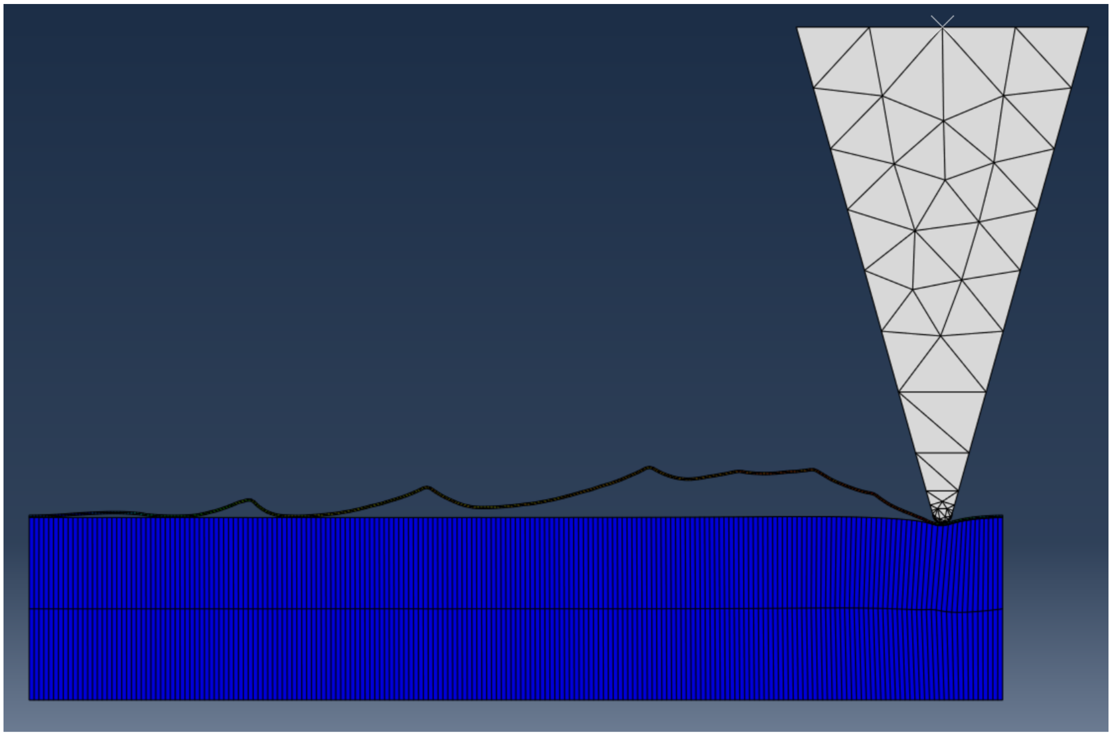
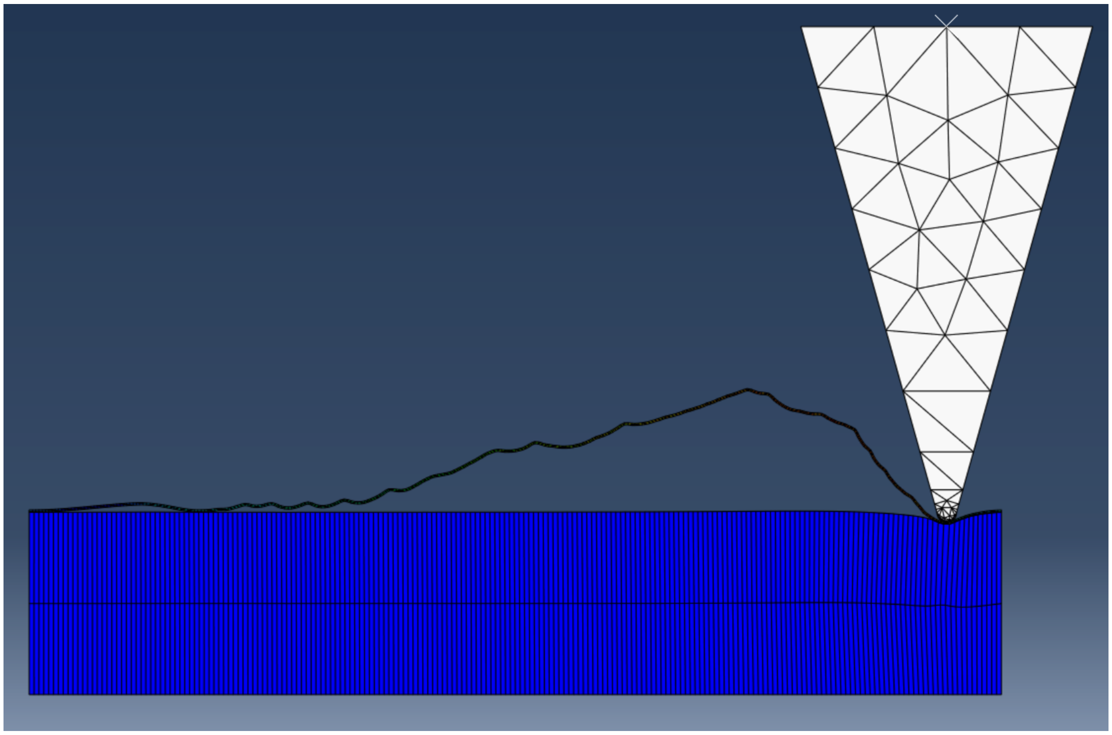
Appendix A: 2D FEA of scratch embossing



This shows the results of using 5 N as the downforce. The blue rectangle represents the rubber backing, and the thin black line represents the TDS.



This shows the results of using 7 N as the downforce. The blue rectangle represents the rubber backing, and the thin black line represents the TDS. Note that buckling behavior is occurring in the TDS.



This shows the results of using 9 N as the downforce. The blue rectangle represents the rubber backing, and the thin black line represents the TDS. Note the higher frequency of the buckles, as compared to the 7 N downforce.

Appendix B: Solenoid Specification Sheet

STA® Push Tubular Solenoids — 1/2" Dia. x 1"

Part Number: 195203 - X XX

All catalog products manufactured after April 1, 2006 are RoHS Compliant

Coil AWG Number
(from performance chart below)

Plunger Configurations and anti-rotation flat on mounting
1 Flat face plunger without anti-rotation flat
2 60° plunger without anti-rotation flat
5 Flat face plunger with anti-rotation flat
6 60° plunger with anti-rotation flat

- Well-suited for battery operation.

See the "Battery Operated Solenoids" section for complete information.

LINEAR Tubular

Performance

Maximum Duty Cycle	100%	50%	25%	10%
Maximum ON Time (sec) when pulsed continuously[1]	∞	50	5	2
Maximum ON Time (sec) for single pulse[2]	∞	140	30	8
Watts (@ 20°C)	4	8	16	40
Ampere Turns (@ 20°C)	497	704	994	1573

Coil Data awg (0XX)[3]	Coil Data Resistance (@20°C)	Coil Data # Turns[4]	VDC (Nom)	VDC (Nom)	VDC (Nom)	VDC (Nom)
27	1.43	306	2.4	3.4	4.8	7.6
28	1.95	342	2.8	3.9	5.6	8.8
29	3.84	508	3.9	5.5	7.8	12.4
30	5.29	572	4.6	6.5	9.2	14.5
31	9.56	795	6.2	8.8	12.4	19.6
32	16.54	1068	8.1	11.5	16.3	25.7
33	22.60	1194	9.5	13.4	19.0	30.0
34	37.41	1547	12.2	17.3	24.0	39.0
35	60.71	1976	15.6	22.0	31.0	49.0
36	96.19	2475	19.6	28.0	39.0	62.0
37	141.93	3060	23.8	33.7	47.6	75.3

1 Continuously pulsed at stated watts and duty cycle
2 Single pulse at stated watts (with coil at ambient room temperature 20°C)
3 Other coil awg sizes available — please consult factory
4 Reference number of turns

Specifications

Dielectric Strength	500 VRMS
Recommended Minimum Heat Sink	Maximum watts dissipated by solenoid are based on an unrestricted flow of air at 20°C, with solenoid mounted on the equivalent of an aluminum plate measuring 2" square by 1/8" thick
Coil Resistance	±5% tolerance
Holding Force	Flat Face:1.00 lb (4.5 N) @ 20°C 60°:0.71 lb (3.2 N) @ 20°C
Weight	0.89 oz (25.2 gms)
Plunger Weight	0.11 oz (3.1 gms)
Dimensions	Ø0.52" x 1.05" L (See page F32)

How to Order

Add the plunger configuration, anti-rotation flat number and the coil awg number to the part number (for example: to order a unit with a 60° plunger configuration without anti-rotation rated for 4.8 VDC at 25% duty cycle, specify 195203-227.

Please see www.ledex.com (click on Stock Products tab) for our list of stock products available through our North American distributors.

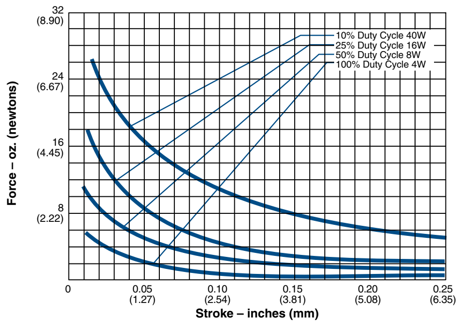
All specifications subject to change without notice.

Ledex® Solenoids F14 www.ledex.com 1.937.454.2345 Fax: 1.937.898.8624

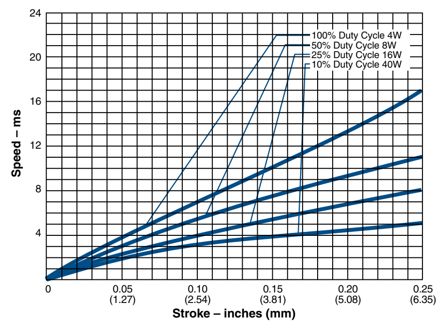
STA® Push Tubular Solenoids — 1/2" Dia. x 1"

Push Tubular Solenoid – 1/2" dia. x 1" – Flat Face Plunger

Typical Force @ 20°C

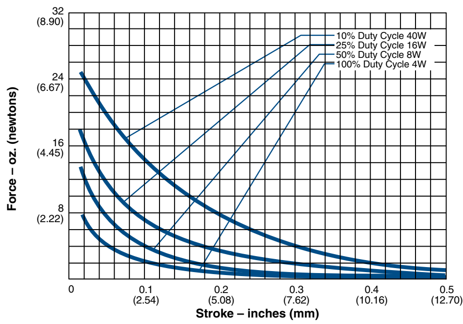


Typical Speed @ No Load, 20°C

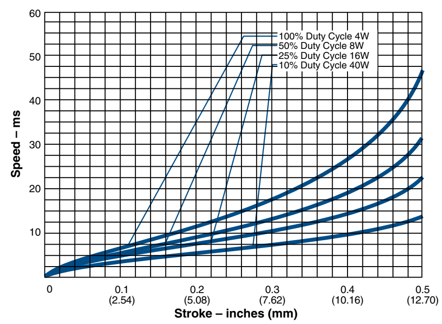


Push Tubular Solenoid – 1/2" dia. x 1" – 60° Plunger

Typical Force @ 20°C



Typical Speed @ No Load, 20°C



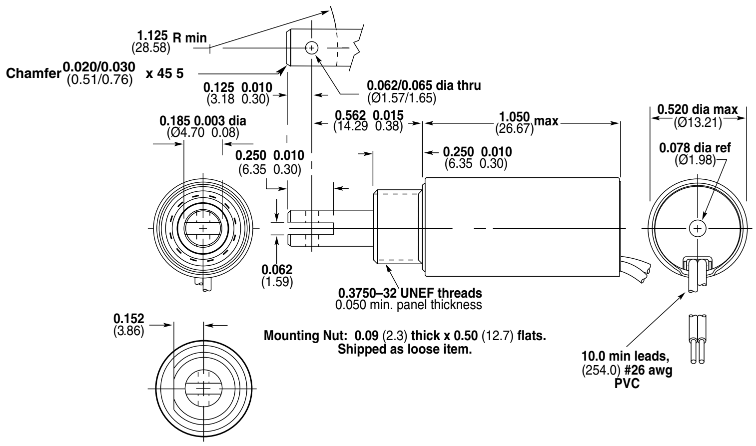
LINEAR Tubular

All specifications subject to change without notice.

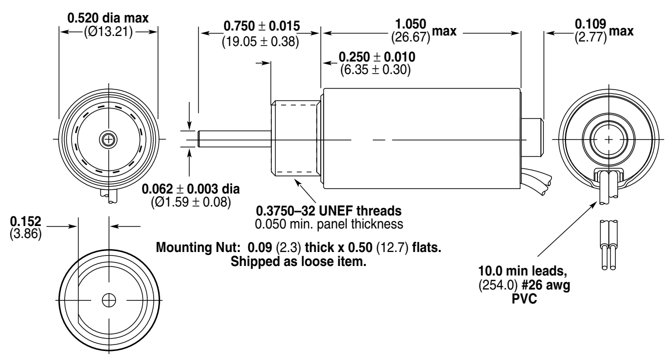
Ledex® Tubular Solenoids Dimensions

Inches (mm)

STA® Series Pull — 1/2" Dia. x 1"



STA® Series Push — 1/2" Dia. x 1"



All solenoids are illustrated in energized state

All specifications subject to change without notice.

Appendix C: Servo Specification Sheet

Famous Professional Servo R&D Manufacturer

HuiDa RC International INC.
Address: 1707,Huashang Building,Xiapu district,Huizhou,Guangdong,China
E-mail:info@chd.hk Tel:86 752 2118844 Fax:86 752 2118860 WWW.CHD.HK

1. **使 用 環 境 條 件**
Apply Environmental Condition：

No.	项目 item	规格 standard
1-1	保存溫度 Storage Temperature Range	-20℃～60℃
1-2	操作溫度 Operating Temperature Range	-10℃～50℃
1-3	操作電壓 Operating Voltage Range	4.8V~6.0V

2. **測 試 環 境**
Standard Test Environment：

2-1	測試環境 Standard Test Environment	每一个检查必须是正常的温度和湿度进行测量，温度 25 ± 5℃，相对湿度 65 ± 10%,在按照本规范的标准测试条件下判断特征。 Every characteristic of the inspect must be normal temperature and humidity carry out the test , temperature 25±5℃ and relative humidity 65±10% of judgment made in accordance with this specification standard testing conditions.

3. **外 觀 檢 查**
Appearance Inspection：

No.	项目 item	规格 standard
3-1	外觀尺寸 Outline Drawing	尺寸见附件 Dimension see the attachment
3-2	外觀 Appearance	无损坏，不允许影响功能 No damage which affects functions allowed

	Product Name	Model No.	Version	Page
Power HD HIGH PERFORMANCE	模拟伺服器 Analog Servo	1501MG	V1	1/3

4. 電 氣 特 性

Electrical Specification (Function of the Performance)：

No.	项目 item	4.8V	6.0V
4-1	空載轉速 Operating speed (at no load)	0.16 sec/60°	0.14 sec/60°
4-2	空載電流 Running current (at no load)	400 mA	500 mA
4-3	停止扭力 Stall torque (at locked)	15.5 kg-cm	17 kg-cm
4-4	停止電流 Stall current (at locked)	2300 mA	2500 mA
4-5	待機電流 Idle current (at stopped)	4 mA	5 mA

注：项目 4-2 定义平均値时，伺服器无负荷运行

Note: Item 4-2 definition is average value when the servo running with no load

5. 機 械 特 性

Mechanical Specification：

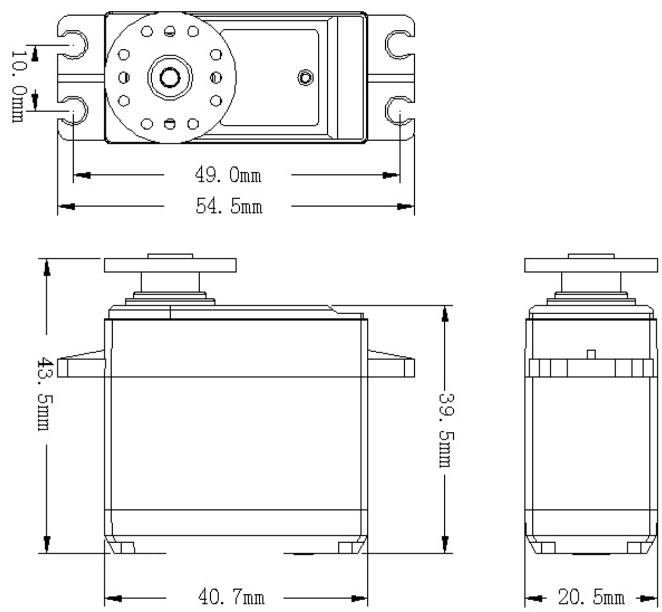
No.	项目 item	规格 standard
5-1	外觀尺寸 Overall Dimensions	见附件 See the drawing
5-2	機構極限角度 Limit angle	180°± 10°
5-3	重量 Weight	63 ± 1g
5-4	導線規格 Connector wire gauge	＃28 PVC
5-5	導線長度 Connector wire length	300± 5 mm
5-6	舵片規格 Horn gear spline	25T/ ϕ 5.80
5-7	舵片種類 Horn type	条型.半臂舵板 Single, Double
5-8	減速比 Reduction ratio	1/298

	Product Name	Model No.	Version	Page
Power HD HIGH PERFORMANCE	模拟伺服器 Analog Servo	1501MG	V1	2/3

6. 控 制 特 性

Control Specification：

No.	项目	规格
6-1	控制系統 Control system	改变脉冲宽度 Pulse Width Modification
6-2	放大器種類 Amplifier type	模拟控制器 Analog Controller
6-3	操作角度 Operating travel	90° (在 1000→2000 μsec)
6-4	中立位置 Neutral position	1500 μsec
6-5	脈波訊號虛位 Dead band width	2 μsec
6-6	旋轉方向 Rotating direction	顺时针 (在 1500→2000 μsec) Counterclockwise (when1500→2000 μsec)
6-7	脈波寬度範圍 Pulse width range	800→2200 μsec
6-8	可作動角度範圍 Maximum travel	大约 165°(在 800→2200 μsec) Approx 165°(when800→2200 μsec)



	Product Name	Model No.	Version	Page
Power HD HIGH PERFORMANCE	模拟伺服器 Analog Servo	1501MG	V1	3/3

Appendix D: Material and component cost

QTY	Percent used	Part Name	Source	Price, each	Cost
2	100%	Dual End-Feed Fastener M5, for 20mm T-Slotted Framing (packs of 4)	McMaster Carr	$ 4.51	$ 9.02
2	100%	Oil-Embedded Mounted Sleeve Bearing Two-Bolt Flange-Mounted,	McMaster Carr	$ 7.97	$ 15.94
1	100%	Oil-Embedded Flanged Sleeve Bearing for 20 mm Shaft Diameter,	McMaster Carr	$ 2.12	$ 2.12
3	100%	Oil-Embedded Flanged Sleeve Bearing for 5/8" Shaft Diameter,	McMaster Carr	$ 1.28	$ 3.84
1	100%	Easy-to-Machine 304 Stainless Steel Rod 5/8" Diameter, 1/2 Feet Long	McMaster Carr	$ 8.83	$ 8.83
1	100%	Tight-Tolerance 6061 Aluminum Rod 5 mm Diameter, 1 Foot Long	McMaster Carr	$ 8.63	$ 8.63
1	10%	Tight-Tolerance 6061 Aluminum Rod 20 mm Diameter, 1 Foot Long	McMaster Carr	$ 20.27	$ 2.03
1	20%	Black Delrin® Acetal Resin Rod 3/4" Diameter, 5 Feet Long	McMaster Carr	$ 2.48	$ 0.50
1	100%	Black Delrin® Acetal Resin Oversized Bar 1/8" Thick, 1" Wide, 1 ft. length	McMaster Carr	$ 2.24	$ 2.24
1	8%	Black Delrin® Acetal Resin Sheet 3/16" Thick, 12" Wide x 12" Length	McMaster Carr	$ 25.30	$ 2.11
1	100%	Power HD High-Torque Servo	Pololu	$ 19.95	$ 19.95
1	100%	3F/H25T Spline Servo to 1/4" Shaft	ServoCity	$ 4.99	$ 4.99
				Merchandise Total	**$ 80.19**

Appendix E: Acetal homopolymer fatigue resistance

Fatigue Resistance

Materials subjected to cyclic stresses sometimes fail at stress levels below their yield strength. This condition is fatigue failure, and the cyclic loading in tension and compression combined is the most severe situation.

Delrin acetal resins have extremely high resistance to fatigue failure from –40 to 82°C (–40 to 180°F). Furthermore, their resistance to fatigue is affected little by water, solvents, neutral oils, and greases.

Fatigue resistance data (in air) for injection molded samples of Delrin acetal resin are shown in **Figures 20** and **21**.

For highest fatigue endurance select Delrin 100. For example, in gear tests, Delrin 100 exhibits approximately 40% higher fatigue endurance than Delrin 500.

Figure 20. Fatigue Resistance of Delrin 500 at 1800 cpm versus Temperature (Air)

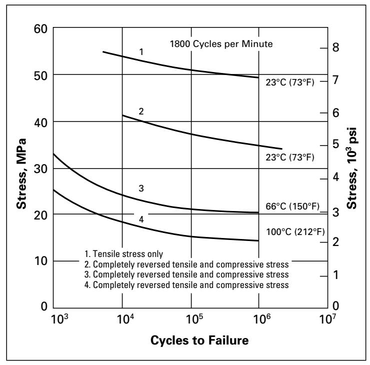
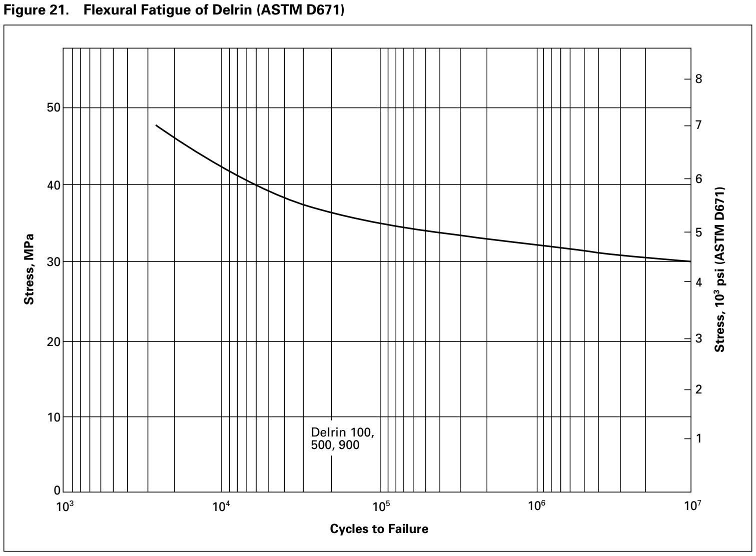


Figure 21. Flexural Fatigue of Delrin (ASTM D671)



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Appendix F: Test Set layout

TEST 1	
Left	Right
2	2
1	4
6	5
1	1
1	6
5	4
5	4
1	2
3	1
2	6
4	6
4	4
4	2
6	3
5	1
3	2
3	4
3	3
2	5
6	6
5	3

Test 2					
A	B	C	D	E	Reference Texture
2	3	6	4	1	1
2	6	3	5	1	3
4	2	3	6	5	6
1	5	3	2	4	2
5	4	3	2	1	6
1	2	5	6	4	5
6	5	2	1	4	6
5	4	1	3	6	2
5	1	6	4	2	4
3	2	1	4	6	5
1	3	4	2	5	2
2	3	5	1	6	4
4	5	3	2	1	1
3	5	4	2	6	1
2	4	1	5	6	3
2	3	6	5	4	4
5	3	6	2	4	5
4	2	3	5	1	3

Test 3		
Left	Middle	Right
7	8	3
11	12	6
9	5	10
12	11	6
5	9	10
12	6	11
3	7	8
9	10	5
5	10	9
6	11	12
8	7	3
6	12	11
8	7	3
7	3	8
10	5	9
3	8	7
10	9	5
11	6	12

Texture #7 and texture #8 are varied degrees of texture #3 (made with the same pattern). Texture #3 has the divots spaced 0.25 in apart, texture #7 has them spaced 0.375 in apart, and texture #8 has them spaced 0.5 in apart.

Texture #9 and texture #10 are varied degrees of texture #5 (made with the same pattern). Texture #5 is made with the Sharp tip, Texture #9 is made with the Standard tip, and #10 is made with the Ball tip.

Texture #11 and texture #12 are varied degrees of texture #6 (made with the same pattern). Texture #6 is made with the Sharp tip, Texture #11 is made with the Standard tip, and #12 is made with the Ball tip.

Appendix G: IRB Exemption 2

Found at: https://www.hhs.gov/ohrp/regulations-and-policy/regulations/45-cfr-46/index.html#46.101(b)(2)

Subpart A - Basic HHS Policy for Protection of Human Research Subjects Authority: 5 U.S.C. 301; 42 U.S.C. 289(a); 42 U.S.C. 300v-1(b). Source: 56 FR 28012, 28022 - PDF, June 18, 1991, unless otherwise noted.

§46.101 To what does this policy apply?

(a) Except as provided in paragraph (b) of this section, this policy applies to all research involving human subjects conducted, supported or otherwise subject to regulation by any federal department or agency which takes appropriate administrative action to make the policy applicable to such research. This includes research conducted by federal civilian employees or military personnel, except that each department or agency head may adopt such procedural modifications as may be appropriate from an administrative standpoint. It also includes research conducted, supported, or otherwise subject to regulation by the federal government outside the United States.

(1) Research that is conducted or supported by a federal department or agency, whether or not it is regulated as defined in §46.102, must comply with all sections of this policy.

(2) Research that is neither conducted nor supported by a federal department or agency but is subject to regulation as defined in §46.102(e) must be reviewed and approved, in compliance with §46.101, §46.102, and §46.107 through §46.117 of this policy, by an institutional review board (IRB) that operates in accordance with the pertinent requirements of this policy.

(b) Unless otherwise required by department or agency heads, research activities in which the only involvement of human subjects will be in one or more of the following categories are exempt from this policy:

(1) Research conducted in established or commonly accepted educational settings, involving normal educational practices, such as (i) research on regular and special education instructional strategies, or (ii) research on the effectiveness of or the comparison among instructional techniques, curricula, or classroom management methods.

(2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

Appendix H: Test Script

General Instructions

- Be sure to stick closely to the scripts below. It is important that each person receives the same instructions and that the exercises are explained using the same language.
- Do not give any feedback that implies that an answer was correct or incorrect. So instead of saying, “good job” or “well done”, say something like “thank you for your effort/focus/attention.”
- If the student is taking a long time, it is okay to offer them an out: “do you want to move on to the next one?”
- It is also okay to guide the students hands to what you are talking about. So for the second test, you can put their hands on the reference texture to make sure they know which one it is.
- Blank sheets are provided on which to record answers
- Please keep a record of students’ identities, associating each with one in a sequence of numbers starting with S302, S303, …
- The test materials are bound in three loose-leaf binders to keep them organized (but need to be removed for the actual trials).
- The instructions for each of the three Tests are included in the binders.

1st Test: Difference

Explanation for the teacher.

For this test, a student is presented with one sheet that has two textures on it. They are asked this question: "Are these textures the same, or are they different?". To ensure that the directions are understood and to ensure that the student has the tactile ability necessary to participate, they are first given one "Qualification Sheet 1" with two radically different materials, and "Qualification Sheet 2" with identical materials. These materials are commonplace items like fleece, shag carpet, sandpaper, leather, etc. – the kinds of stuff used in making one-off tactile maps, for example.

If the student is not able to answer the Qualification Sheets correctly, they be given some free-hand drawing time for fun, but will not continue with the texture study. A student who correctly responds to the first two practice sheets moves on to familiarization with textures made on the tactile drawing film (and learn by example what "texture" means).

During the formal texture comparisons, the teacher checks boxes to record the student's answers on a separate answer sheet – formatted in inkprint or Braille as needed.

Script for the teacher (don't say the numbers)

1. Okay (Student Name) let's get started. I am going to give you some textures to feel and ask you some easy questions about them. There's no right or wrong answer; we are just trying to learn how these textures feel to you and other people. So, I am going to have you feel textures two at a time; you are going to tell me if they are the *same* or if they're *different* from each other. That's all. Does that make sense to you?

If "yes", go to 4. If "no", continue with 2.

2. Okay, I'll say it in a different way. I am going to put a sheet in front of you that has two textures on it. I just want you to tell me whether they feel the same different. Does that make sense?

If yes, go to 4. If "no…

3. try to re-phrase at your discretion.

If they understand, go to 4. If "no", provide fun drawing experiences but discontinue the trial with this student.

4. Great. First, let's practice with this sheet.

Give student Qualification Sheet 1 with fleece and rough cloth. The correct answer for this sheet is that the textures are different.

T: Are these two textures the same, or are they different?

Note response. Replace the sheet with "Qualification Sheet 2" that has two pieces of fleece. The correct answer for this sheet is that the textures are the same.

T: What about on this sheet? Are these two textures the same, or are they different?

Note response. If the student gets both Qualification Sheets correct, move on. If not, reiterate instructions, ask if they understand, and try again. If they still give the wrong answers, provide fun drawing experience but discontinue the trial with this student

T: Okay, so now I am going to give you two textures made on the drawing sheet to practice on.

Give student first sheet from Familiarization Set.

T: Are these two textures the same, or are they different?

Continue giving the student sheets from the Familiarization Set until there are none left. It doesn't matter what their answers are in this phase.

T: Do you feel like you have practiced enough to start, or do you want some more practice?

Allow student to continue to practice if they choose. Stop when they say they are ready, or when they have gone through the Familiarization Set a second time, whichever happens first.

T: Okay, now we are going to start. Remember that there are no wrong answers.

Give student the first sheet from the Test Set.

T: Are these two textures the same, or are they different?

Record response on answer sheet.

Continue giving the student sheets from the Test Set until there are none left.

Congratulate, celebrate, and thank as appropriate.

2st Test: Recognizability

Explanation for the teacher.

This test will operate in the same sort of way as the first. Students will be given one sheet with a reference texture on the right side and a line separating it from a group of five textures (potential matches). The goal of the exercise is to determine which texture out of the potential matches is the same as the reference texture. It is also possible that the reference texture will not appear in the set of potential matches. The students are asked, "which one is the match for the texture at the top-right, or is there no match on the page?"

Again to ensure that the instructions are understood and that the student has the tactile ability necessary to participate, students are first given "Qualification Sheet 1" where the reference texture is on the sheet, and "Qualification Sheet 2" where it isn't. On these sheets, the materials are commonplace items like fleece, shag carpet, sandpaper, leather, etc. – the kinds of stuff used in making one-off tactile maps, for example. After correctly answering the example sheets, the students will be allowed to practice with textures made on the tactile drawing film before the test begins. The teacher will be recording the student's answers in a separate answer sheet, which will either be a tactile drawing sheet or a print answer sheet.

If the student is not able to make the practice comparison correctly, they be given some free-hand drawing time for fun, but will not continue with the texture study. A student who correctly responds to the first two practice sheets moves on to familiarization with textures made on the tactile drawing film.

During the formal texture comparisons, the teacher checks boxes to record the student's answers on a separate answer sheet – formatted in inkprint or Braille as needed.

Script for the teacher (don't say the numbers)

1. Okay (Student Name) for this next exercise you are going to try to find the match for a texture. So this sheet has one texture at the top-right that is apart from the others. I want you to feel that texture and see if you can find its match somewhere else on the page. Some of the time, there might not be a match on the page, so tell me if you can't find it. Does that make sense to you?

If "yes", go to 3. If "no", continue with 2.

***2**. try to re-phrase at your discretion.*

If "yes", go to 4. If "no", provide fun drawing experiences but discontinue the trial with this student.

3. Great. First, let's practice with this sheet.

Give student the "Qualification Sheet 2.1" which has the fleece as the reference texture. The correct answer for this sheet is that the match is in the center-top position.

T: Can you find the match for the texture on the right?

Note response. Replace Qualification Sheet 2.1 with "Qualification Sheet 2.2" which has felt as the reference texture. The correct answer for this sheet is that there is no match.

T: What about on this sheet? Can you find the match for the texture on the right?

Note response. If the student gets both practice sheets correct, move on. If not, reiterate instructions, ask if they understand, and try the practice sheets again. If they still give the wrong answers, provide fun drawing experience but discontinue the trial with this student

T: Okay, so now I am going to give you examples with the textures made on the drawing sheet to practice on.

Give student first sheet from Familiarization Set.

T: Can you find the match for the texture on the right?

Continue giving the student sheets from the Familiarization Set until there are none left. It doesn't matter what their answers are in this phase.

T: Do you feel like you have practiced enough to start, or do you want some more practice?

Allow student to continue to practice if they choose. Stop when they say they are ready, or when they have gone through the Familiarization Set a second time, whichever happens first.

T: Okay, now we are going to start. Remember that there are no wrong answers.

Give student the first sheet from the Test Set.

T: Can you find the match for the texture on the right?

Record response on answer sheet.

Continue giving the student sheets from the Test Set until there are none left.

Congratulate, celebrate, and thank as appropriate.

3rd Test: Degree

Explanation for the teacher.

This test will operate in the same sort of way as the first two. Students will be given a sheet with three textures on it. The textures will all be very similar in terms of pattern, but they will increase in either the spacing of the pattern, the characteristics (height/sharpness) of the lines. These groups of texture would be used to indicate increasing amounts of some property, like population density on a map. For this section, students will be given a sheet with three textures on it, and they will be asked to list them from "least" to "most." This is intentionally left vague, so that the students can decide for themselves the order of the textures without being influenced by language like "denser" or "darker."

The students will be allowed to practice with textures made on the tactile drawing film before the test begins. The teacher will be recording the student's answers in a separate answer sheet, which will either be a tactile drawing sheet or a print answer sheet.

If the student is not able to make the practice comparison correctly, they be given some free-hand drawing time for fun, but will not continue with the texture study. A student who correctly responds to the practice sheets moves on to familiarization with textures made on the tactile drawing film.

During the formal texture comparisons, the teacher checks boxes to record the student's answers on a separate answer sheet – formatted in ink print or Braille as needed.

Script for the teacher (don't say the numbers)

1. Okay (Student Name) for this next exercise I am going to give you a sheet that has three textures on it, and I want you to rank three textures from least to most. Does that make sense to you?

If "yes", go to 3. If "no", continue with 2.

2. So I want you to tell me the order that makes the most sense to you for the three textures, from least to most. Whatever that means to you. Does that make sense?

If "yes", go to 4. If "no":

3. try to re-phrase at your discretion.

If they understand, continue to 4. Otherwise, provide fun drawing experiences but discontinue the trial with this student.

4. Great. First, let's practice with this sheet.

Give student the "practice sheet" that has with three grits of sandpaper. The correct answer is in order of increasing grit particle size. If the student gets the Qualification Sheets correct, move on. If not, reiterate instructions, ask if they understand, and try again. If they still give the wrong answers, provide fun drawing experience but discontinue the trial with this student

T: Okay, so now I am going to give you examples with the textures made on the drawing sheet to practice on.

Give student first sheet from Familiarization Set.

T: Can you tell me the order of these three from least to most?

Continue giving the student sheets from the Familiarization Set until there are none left. It doesn't matter what their answers are in this phase.

T: Do you feel like you have practiced enough to start, or do you want some more practice?

Allow student to continue to practice if they choose. Stop when they say they are ready, or when they have gone through the Familiarization Set a second time, whichever happens first.

T: Okay, now we are going to start this section. Remember that there are no wrong answers.

Give student the first sheet from the Test Set.

T: Can you tell me the order of these three from least to most?

Record response on answer sheet.

Continue giving the student sheets from the Test Set until there are none left.

Congratulate, celebrate, and thank as appropriate. Give the student the gift card as a thanks for their time.