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Sensitive Calligraphy Robot & Design Review Creation

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Sensitive Calligraphy Robot & Design Review Creation

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CONTENTS

Sensitive Calligraphy Robot

Development of a Platform for Combined Force & Position Control

Introduction: Calligraphy Robot

The calligraphy robot was developed as a proof-of-concept for a compliant platform with a control system that maintains accuracy of position. The end-effector was designed to utilize a rotary series elastic actuator (SEA) for compliance and force-sensing. The mechanical system that supported the end-effector was a gantry system designed for smooth motion and accurate positioning. The mechanical platform and force-sensing software were designed to support the full integration with a PVT controller. The PVT software that created the motion paths and controlled the accuracy of the positioning was not a part of this MQP. It was programmed by Ennio Claretti and Allen Blaylock who were part of the team that prepared this robot for the Cornell Cup Competition.

The Cornell Cup Competition, presented by Intel, accepts 30 teams from universities across the United States to participate in an embedded design competition that spans one academic year and culminates in an exposition and final judging. The competition required several design reviews to be conducted over the development of the design, in order to mimic a professional engineering process. However, there is not a significant body of examples and references that are helpful guides to critically approaching the creation of a design review. The Cornell Cup design reviews formed the analytical basis for a study on the choices that must be made during their creation and the forces that influence those choices, which culminated in a handout guide to help other students improve their design reviews. This study is included in Appendix A of the report.

Motivation & Background

Current robotics research tends to focus on either stiff, position-precise control or compliant, force-sensing control. However, there are tradeoffs between these two alternatives. Stiff robots have difficulty interacting with their environment and compliant robots have increased uncertainty in their positioning. I proposed a calligraphy robot to write in shaded scripts as a proof-of-concept for a system that combines both precision-position control and precision-force control.

In order to interact with the world in a productive manner, robots need some way of obtaining information about the word. Traditionally, robots relied upon the creation of an accurate model of the world it was situated in via hard coding or vision sensors. The vision systems however often required very controlled environments – for example: simplified geometry, enhanced contrast, and specialized lighting [1]. Pure vision based systems are prone to many challenges including the tendency towards uncertainty and missing data [2].

To control the motions of the robot, the traditional approach has been to create stiff systems that can be controlled with high levels of precision [3]. However, while the joints of these systems have high precision, they are unable to safely interact with objects, humans, and dynamic environments. When the robot approaches an object, its motion must slow down or risk a high speed collision that could damage both the object and robot [3]. Some systems try to use force control to manage interactions with objects. However, stiff systems are prone to oscillation or "chatter" when they attempt to come into contact. This contact instability can thwart attempts to use force control [4].

An alternative method to manage environment interactions uses compliance instead of stiffness. [4], [5], [3], [6]. Compliant means that there is some "give" upon contact. However, the nature of compliance reduces the precision of position control. The added uncertainty reduces the control over the robot's motion paths and can make manipulation difficult. A challenge is to integrate precision position and sensitive force control together into a system enhances the advantages and reduces the weaknesses of each system by combining them together.

Applications of Control System for Calligraphy

Writing calligraphy is a good context for combined precision position and precision force controls. Calligraphy is a very difficult task for humans because it requires well-honed fine motor skills and well-trained muscle memory to produce identical strokes repetitively. The International Association of Master Penmen, Engrossers and Teachers of Handwriting (IAMPETH) currently recognizes only 15 individuals in the world as Master Penmen [7]. Precision of position is crucial to the art form of the calligraphic scripts. **Figure 1** below shows an example of a shaky, poorly formed Autopen signature on the left compared to a normal signature, shown right, that demonstrates the fluidity expected of letters written with some skill.

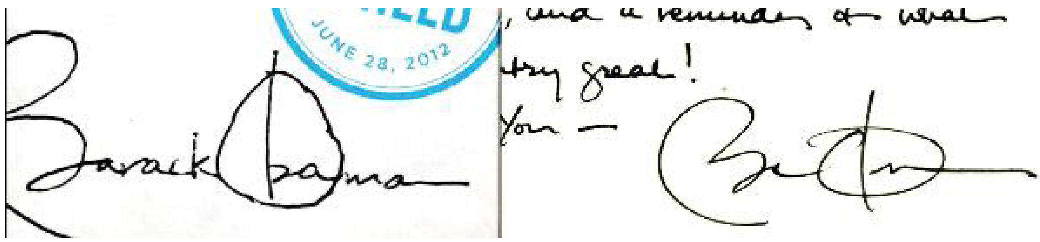

Figure 1: Comparison between an Autopen signature (left) and a genuine signature (right). Note how the 'O' on the left is shaky and uneven.[8]

Shaded scripts are a classic element of calligraphy that requires precise force control. "Shaded" means that letters are made up of lines that have multiple widths. Varying these widths relies on applying exact, specific forces to the pen nib to achieve the desired stroke width (Figure 2 below shows varying widths). The only way to create smooth, legible, and artistic fonts that are free of shakiness, wiggles, gaps, or blotches is to use high precision force control and position control together with a very high level of precision.

Figure 2: An example of a shaded script font. Note how the widths of the strokes vary. [28]

The range of forces applied to the pen nib are determined by how far apart the tines can spread while maintaining the capillary action that draws the ink down the slit onto the paper. The width of the stroke depends on the force applied and the flexibility of the pen nib. In an initial testing, two different pen nibs exerted 2.5N and 6N respectively on a force plate to draw the same line width. The nibs can take more force without breaking to an extent; however, the capillary action that draws the ink down the pen still to the tip will fail if the tines are forced too far apart. The tines and slit are labeled in the below in **Figure 3.** The shape and action of the pen nib means that wide strokes must be written with a top-to-bottom pulling motion; the opposite will result in the pen jamming into or skipping along the paper, ruining the stroke.

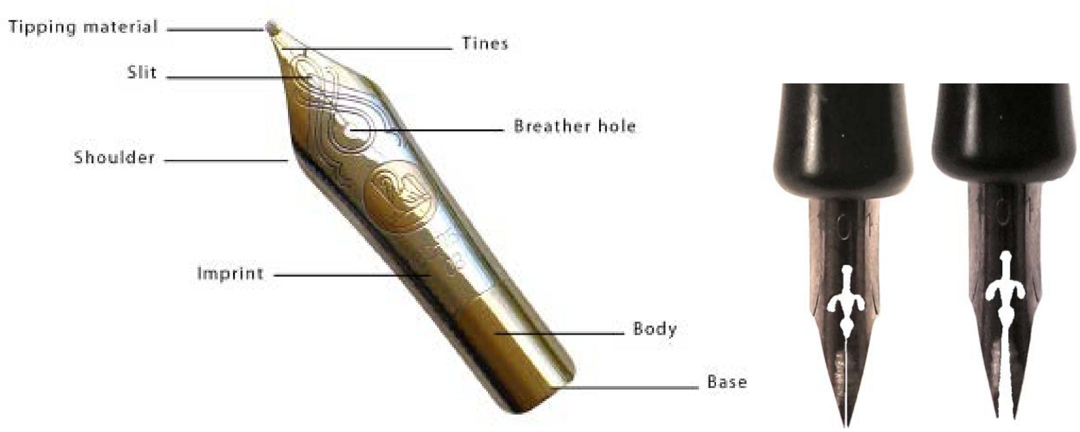

Figure 3:[LEFT] A labeled anatomy of a typical pen nib. [9] The ink flows down the slit to the tip of the pen. [RIGHT] The tines on a relaxed pen nib are nearly touching, which will create a thin line. When the nib is pressed against a writing surface, the tines spread apart which will draw a thicker line. If they spread too far apart, the capillary action will be broken and the ink will not be able to flow.

Possible Applications for Surgical Robotics

This combined control system can be transferred across domains and be applicable in many other fields. The situations that face surgical robots have many similarities. The task of cutting incisions with a scalpel requires dexterity through precise position control, sensitivity to contact by sensing the force, balance between position and force control, and smooth and continuous motions. The cutting and writing motions are also directionally dependent – significant forces must be applied via a pulling motion. Knives and pens can be grasped in a similar fashion, especially from a robot's point of view, which means the mechanical setup has potential for transfer as well, not just the controls system. In addition to the challenge of improving current robotics control systems, the obvious opportunities for further applications increased the worthiness of this project

The balance between precise control of position & force is critical to the success of medical robots. Those that work within bodies have been improved by the addition of force feedback [10]. Some robots assist with cutting incisions. Cooperative surgery robots work together with the surgeon to manipulate the tool [11] or provide a haptic interface device for the surgeon [12]. However, the robots cannot make incisions independently because they lack the ability to feel the skin which is crucial when making an incision do to variations in skin thickness and density between people. The cuts must cut cleanly through the skin without disturbing the delicate organs underneath, which dictates a smooth, continuous motion and the exact application force. There have been studies on integrating force and position sensors into incision tools [13],[14], [15], and it remains an open field of research.

TASK AND SCOPE

The scope of the system is the ability to write smooth curves that cleanly fluctuate in width without tearing the paper or damaging the pen nib. The requirements for successful calligraphy demonstrate the difficulty of the task and the necessity for a combined control system. These include:

1) Integrate and balance position and force control to achieve accuracy while retaining the ability to come into contact with the environment.
2) Transition across even intervals of a small force range.
3) Move smoothly between commanded points to achieve fluid lines.

While the system is a "calligraphy robot", creating the Bezier curves to define the font was beyond the time limits of this project. The Bezier curves used for this project are approximately equivalent to the curves used within letters; it just took far less time to define a few generic curves than to go through each letter of the alphabet which can consist of many connected curves. The robot was able to successfully meet these three requirements.

DESIGN OVERVIEW

There are 3 main components to the robot: the single-axis end-effector, the 3-axis gantry system, and the control architecture of motors, sensors, and controllers. Figure 4 shows a sketch of the configuration and the four axes of motion. I kept the cost low by assembling the majority of the robot with readily available commercial off the shelf (COTS) parts. The several custom parts, including the pen holder, motor clamps, and rotation joint, were 3D-printed. The low cost and available parts also make the design more reproducible which should facilitate future upgrades and applications in other research domains.

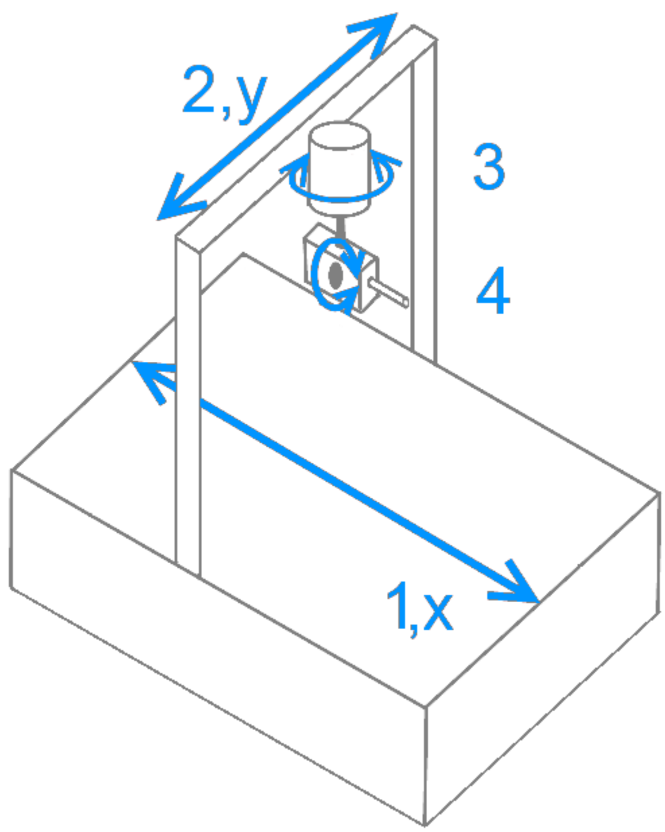

Figure 4: The 4 axes of motion for the design. There are two linear motions (1, 2) and two rotational motions (3, 4).

The system has the following features:

- An end-effector with a rotary Series Elastic Actuator (SEA) for compliance and force sensing.

- Force sensing over a range of 0-4N with a resolution of 0.013N.
- A 2-axis, low-friction gantry system with linear bearings and rigid connections to prevent undesired twisting or shaking.
- A screw-drive x-axis with a 0.01mm position resolution.
- A belt-drive y-axis with a 0.06mm position resolution.
- Encoders on motors connected to axes 1, 2, and 3. A rotary potentiometer on axis 4. A linear potentiometer mounted to the SEA.
- PVT positioning software via a Maxon EPOS controller.
- PD control loop for force-sensing on a Arduino Uno.
- An Intel Atom board with Windows and Matlab software that manages the communication throughout the control architecture.

The full CAD model of this design is shown below in Figure 5. The pen holder end-effector is shown mounted on the rotation axis in the callout. The rotation axis is mounted to the linear belt-drive. The linear belt-drive is then mounted on two support posts which are attached to the linear bearings connected to the screw drive. The linear screw drive is mounted beneath the writing surface. The base of the robot is a box to hold the electronic components.

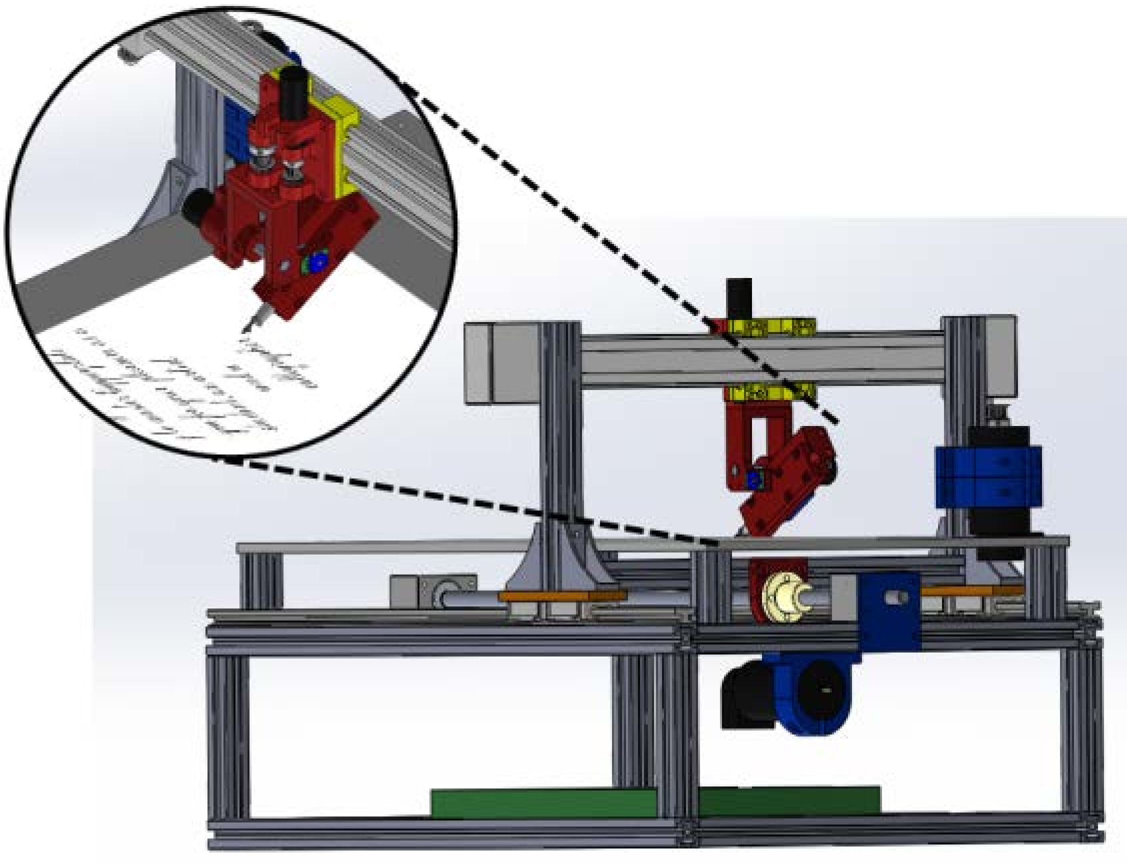

Figure 5: The CAD model of the complete robot design. The pen holder end-effector is shown mounted on the rotation axis in the callout. The gantry system is mounted on top of a box frame that holds the electronic boards.

The End Effector

The end effector is made up of the fountain pen, custom pen holder, the SEA, and two potentiometer sensors. There were two driving components to the design of the pen holder: the series elastic actuator and the pen itself. The two were combined into a single end-effector that could be easily mounted securely to the rotational axis.

The Pen

I chose to use a fountain pen rather than a dip pen. Flex nibs, where the tines spread more easily and farther apart, are more readily available in dip pen form. However, as the name implies, dip pens must be dipped in an inkwell. Dipped pens can only hold as much ink as it takes to coat the nib – they cannot write much longer than 1-2 words before needing to be re-dipped. This is a nuisance and would have required a system to detect when the pen was out of ink or simply re-dipped after every few curves. It would have also required a mechanical system to lower into and raise the pen from the inkwell. This mechanical system was not needed to satisfy the overall task of this project, so an alternative that would simplify the design was preferable.

Fountain pens that have a similar flexibility to the flex dip pens tend to be vintage fountain pens that cost $150 or more. [29] However, several calligraphy forums recommended the Noodler's Ahab fountain pen as an adequate flex nib for beginners. Its nib is stiff compared to some of the most flexible dip pens, but does create a noticeable range of widths (Figure 6).

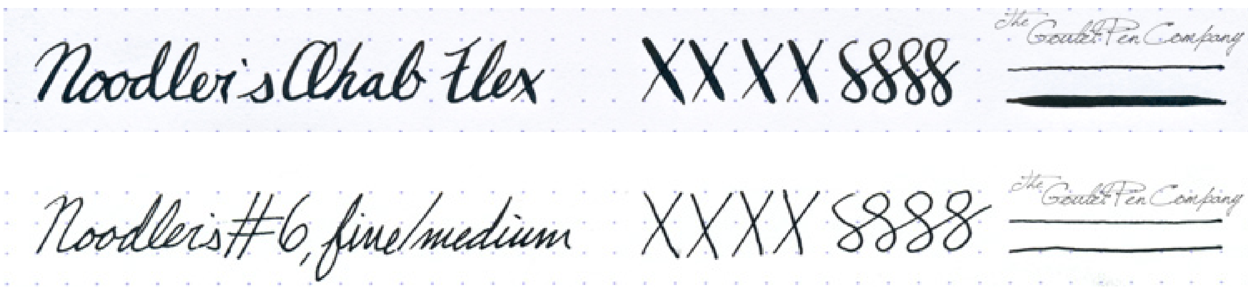

Figure 6: The top image shows the range of the line widths that can be written with the Ahab fountain pen. [30] The bottom shows an example of a more typical inexpensive fountain pen that does not show the variation of width.

The Ahab holds a full 6 ounces of ink with an eyedropper conversion that stores ink in the entire body of the pen. Rubber o-rings and 100% silicone grease seal the threads that the body screws onto in order to prevent the ink from seeping out. The difference between a normal ink reservoir and an eyedropper conversion are shown in Figures 7 and 8.

Figure 7: On the right, the body of the pen is removed to show the internal reservoir. The pen on the left has been converted. The internal reservoir was removed and the entire body acts as a reservoir instead.

Six ounces of ink is a significant amount (Figure #) – more than enough to write multiple lines, or multiple pages of text, and for the user to determine when a refill is necessary.

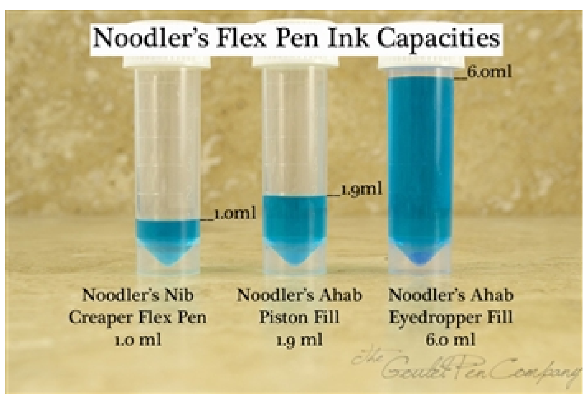

Figure 8: The middle vial shows how much ink a normal Ahab pen with the internal reservoir holds. The vial on the right shows how much ink the pen can hold after the eyedropper conversion. [30]

Furthermore, this pen cost a reasonable $20, with an additional $4 expense for the eyedropper conversion. In summary, the Noodler's Ahab fountain pen was affordable, long-lasting, simplified the mechanical design, and satisfied the need for a flex nib. Therefore it was chosen as the main pen for the project.

The Ahab's force range was measured by drawing on a sheet of paper placed on top of a Vernier force plate. The measured forces were recorded with LoggerPro software and the resultant graph is shown below in Figure 9. The graph shows that at above 4N of force the tines splayed too wide, breaking the ink flow. Therefore, the pen nib operates within the range of 0-4N.

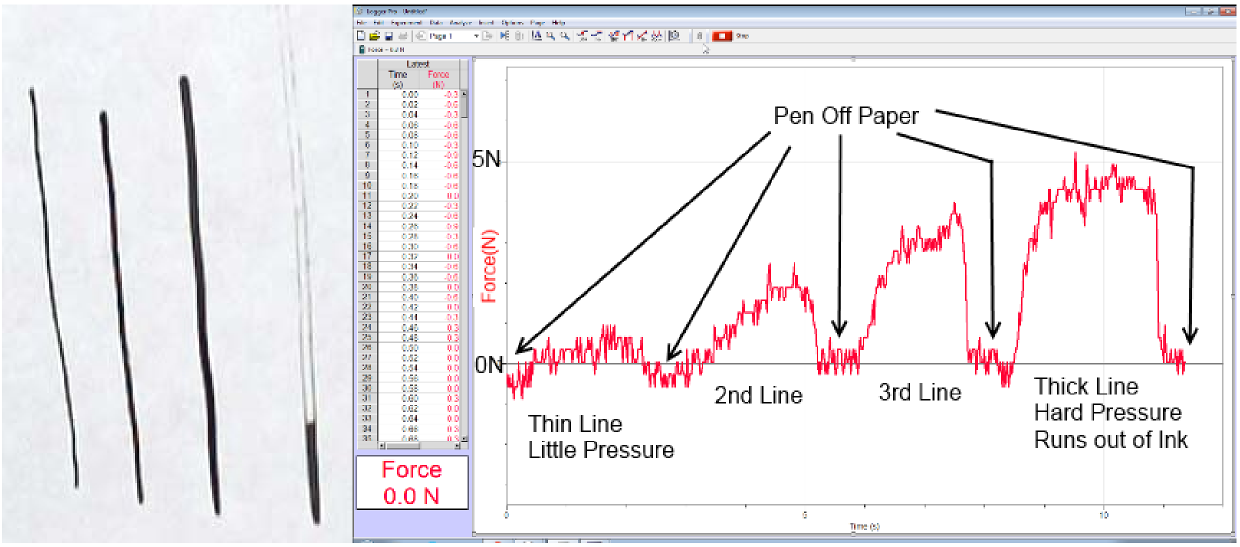

Figure 9: [LEFT] Four lines of varying widths drawn on top of a force plate. [RIGHT] This graph shows the forces recorded while the 4 lines were drawn. The maximum force that maintains the pen's capillary action does not exceed 4 Newtons of force.

Finally, I measured the approximate angles at which I held the pen, to determine the range of rotation that would need to occur around axis 4. When the pen is held in the traditional Spencerian manner (Figure 10), the angle is between 25-40 degrees.

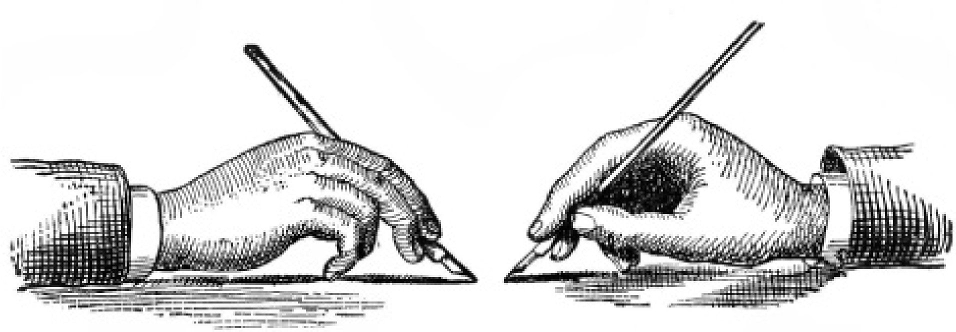

Figure 10: A graphic from a Spencerian handbook demonstrating how to hold a calligraphy pen. [31]

Pen Holder

The end effector holds the pen securely in place and houses the springs and potentiometers for the SEA force-sensing system. This was one of the most difficult parts to design; 3 full prototypes and several more partial prototypes were developed and tested before concluding on the final design. Several of these rejected prototype designs are shown below in Figure 11.

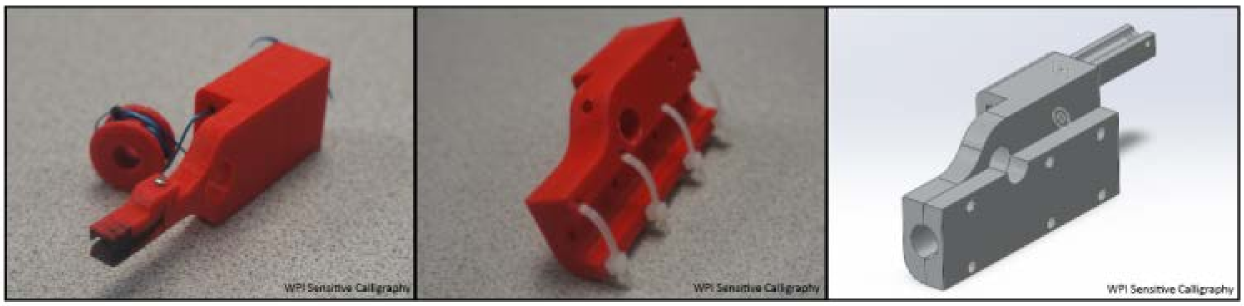

Figure 11: Three rejected prototypes. [LEFT] A prototype intended to hold a dip pen nib without a pen body. [CENTER] A prototype that held a fountain pen by the ad hoc usage of zip ties fed through an arched hole. [RIGHT] A prototype that clamps the pen into place with a plate attached via screws and has the linear potentiometer protruding off the back of the holder.

Parts that were 3D printed with PLA material on a Makerbot Replicator 2 had certain limitations:

- The tolerances were not consistent; holes were sometimes smaller than intended. This was compensated for by increasing the number of shells to 5 or 6. This allowed for holes to be drilled out or filed if necessary.
- Holes could be tapped. However, if the screws were removed and replaced several times, the threads had a tendency to strip. Heat-inserted metal threads did not strip, but were nearly impossible to place in exact alignment with corresponding holes. The design limited the number of screw holes.

However, the softer and more malleable nature of the PLA made press fits easy to implement and very secure. The final design for the pen holder has a single, slightly-tapered hole that the fountain pen is pressed into by hand, which holds it quite securely. There are two set screws that can be used to further clamp onto the pen, however these are a mechanical redundancy.

The housing for the springs juts off to the side of the pen holder. This provided a space to mount the cabling pulleys in line with the springs (Figure 12). The configuration of two springs in line with each other and cabled to pulleys will be discussed in greater detail in the Series Elastic Actuator section. To keep the pen-holder design compact and robust, the linear potentiometer is mounted beneath the pulleys and spring housing where it is tucked away. When the pen holder is rotated between 25-40 degrees, as determined with the fountain pen, the linear potentiometer does not interfere with the pulleys.

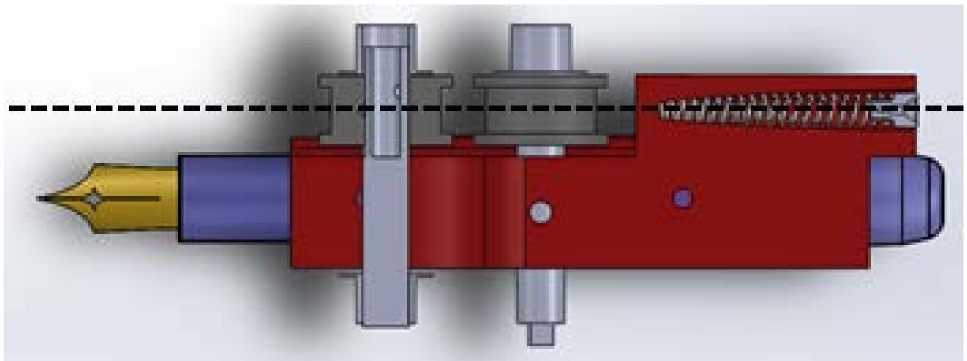

Figure 12: A top view of the pen holder. The black dashed line shows how the springs (vertically aligned and partially revealed in cross-section view) are mounted in line with the pulleys (dark gray) that are used for cabling the SEA.

The linear potentiometer is connected to the spring by a spring cap with an extrusion (Figure 13). The extrusion has a hole that the potentiometer’s shaft fits into. It is then clamped into place by a nut on either side of the extrusion. The bridge between the cap and extrusion travels along a slot in the side of the spring housing. This spring cap is the only part that requires customized CNC machining. It is critical that it is made of a stiff metal to prevent bending or twisting that could interfere with the measurement of the spring deflection, which is used for the force sensing program.

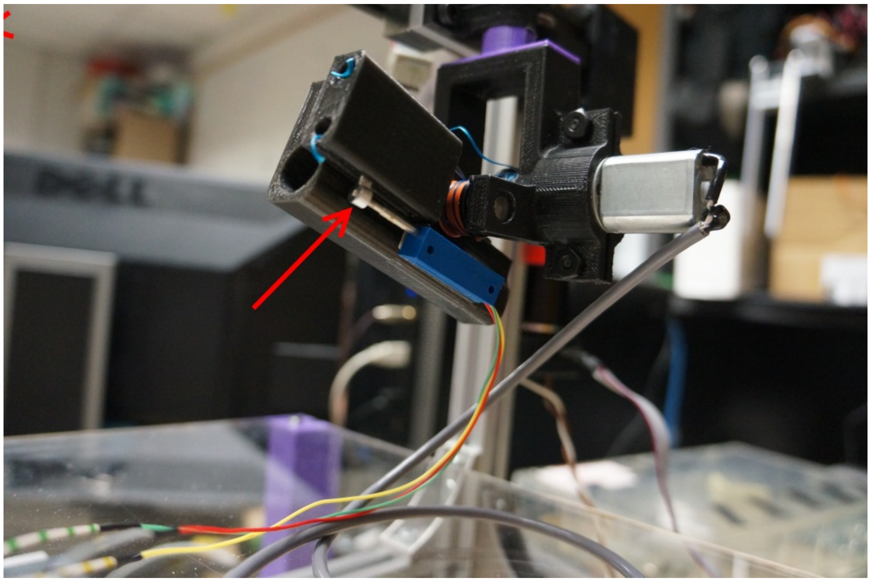

Figure 13: The spring cap in the pen holder, attached to the linear potentiometer. The accuracy of the force control relies on the piece being very stiff to avoid bending or twisting.

Series Elastic Actuator

Series elastic actuators (SEAs) use flexible springs that deflect when force is applied to the end effector. [16], [6] The SEA puts the springs between the motor and the load (end-effector) which decouples them from each other (Figure 14). This means that the end-effector can move slightly without the motor moving. In other words, the end-effector has some “give”, also known as compliance. When no force is applied to the end-effector it moves in sync with the motor, so there is no deflection in the springs. When a force is applied to the end-effector and the motor is held in place, the springs will deflect according to the spring equation below, where F is the force applied *to the springs*, delta x is how much the spring is deflected, and k is the spring constant:

$$F = \Delta x * k$$

The springs have a known *k* value. Therefore by measuring Δx, the software can derive the force F that is applied to the load. [17] The *k* value for the springs in this design was based on the maximum force of 4N that the system needed to measure and apply.

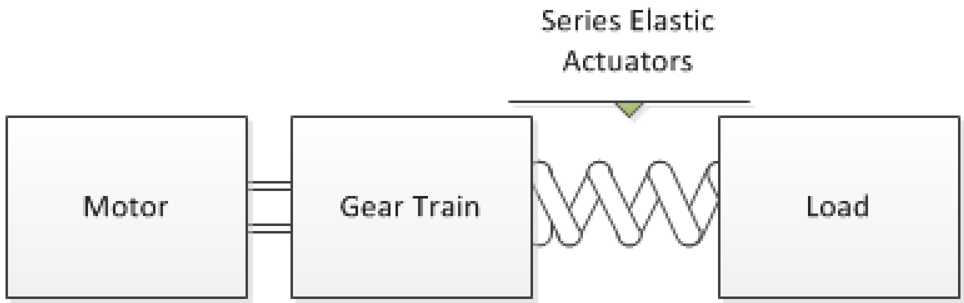

Figure 14: This shows the placement of the SEA springs in relation to the load (in our case, the pen holder) and the motor. This placement provides compliance and allows for force-sensing.

There are both linear and rotary versions of SEAs. While original SEAs that utilized ball screws or custom-made torsional springs could be very costly, a newer SEA design utilizes two opposing linear springs coupled to a rotary shaft (Figure 15 below) [17]. This design is easily miniaturized and is convenient for mounting onto rotational joints – such as the axle my pen holder is mounted on.

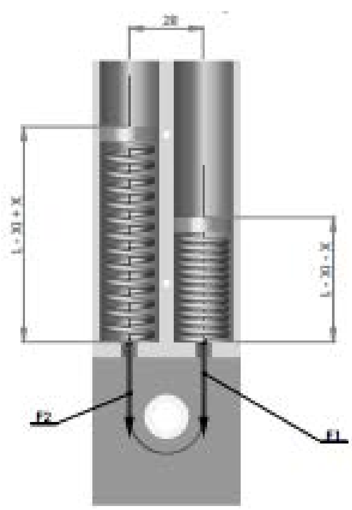

Figure 15: An illustration of a rotary Series Elastic Actuator. The rotating joint is at the bottom. As it rotates, it compresses one spring and the other spring relaxes. At equilibrium, both springs are at half-compression. This way the system will never attempt to make them go beyond 0 compression or full compression.

I designed the configuration of the pen holder prior to choosing springs. The springs and the tip of the pen nib physically had to be offset from the axis of rotation. The amount of offset varied the torques that would be at play in the system, and the torque scales the force on the pen nib to a different magnitude of force applied to the springs. I changed the offset values and the maximum deflection of the spring, and calculated the required k value for the minimum and maximum angle of contact. I compared the spring radius, compression distance, and k value variable sets until I found a spring that satisfied all 3, was readily available, and within budget. The calculations for the final set of values are shown in Figure 16.

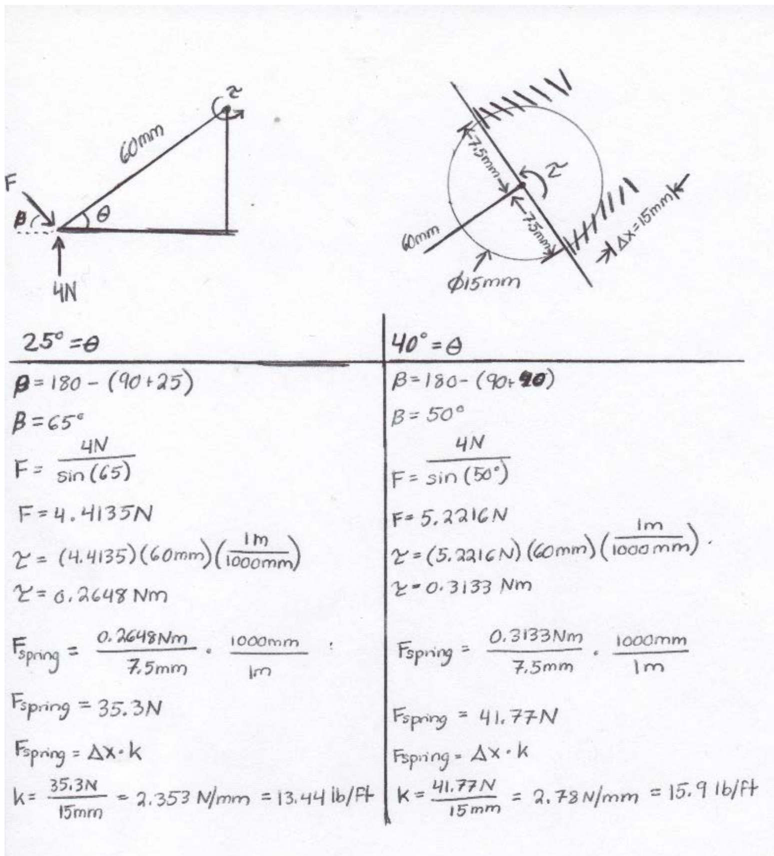

Figure 16: This shows the math to find a desired spring constant (k) for a pen length of 60mm, a spring offset of 7.5mm, and a spring stroke of 15mm for the minimum and maximum pen angles. The math shows I needed a spring with a constant somewhere between 13.4 and 16 lbs./ft.

However, after testing these springs, they proved too stiff to accurately detect the very small forces needed to draw the hairline strokes. I found a spring with the same compression length and approximately the same diameter, but with a *k* value of 9.7 lbs/ft. Saturating this spring to its full compression is sufficient to draw a sufficiently wider line to satisfy the goals of this project.

The final configuration of the SEA within the pen holder is shown below in Figure 17.

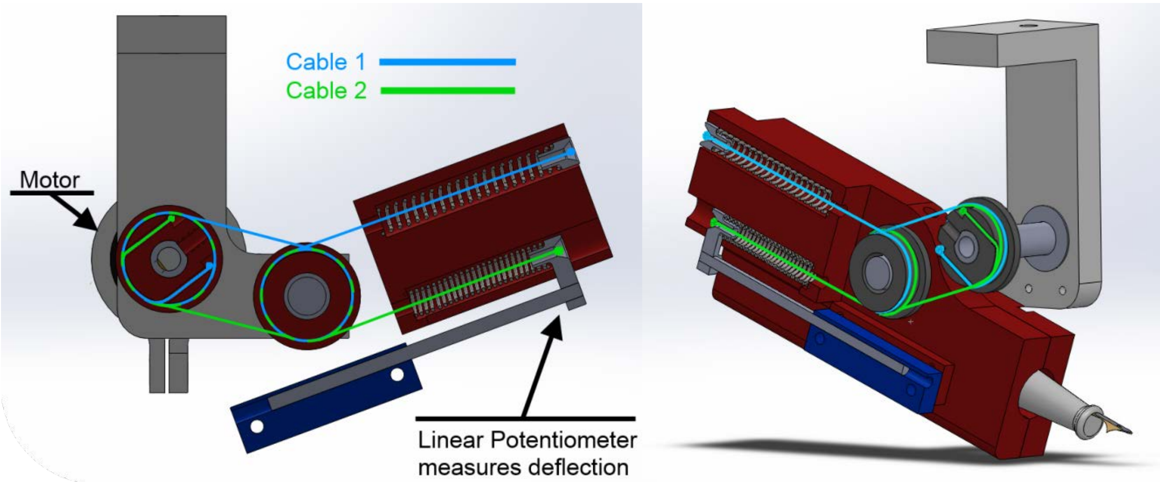

Figure 17: A cross-section view of the end-effector that shows how the series elastic actuator is cabled. The middle pulley is locked in phase with the pen holder. When the motor holds in place, that pulley does not spin, so that when a force is applied to the pen nib, the pen holder and its corresponding pulley do rotate, and this changes the compression on the spring. The linear potentiometer measures this deflection to determine the force applied.

SUPPORTING BRACKET

Finally, a bracket was designed to hold the pen holder and motor. It also acted as the mounting point to axis 3, or the rotational axis. For ease of assembly, the motor is clamped into place on the side of the bracket. The bracket supports each axle on both sides to increase the stability of the design. A rotational potentiometer was added to the pen holder's tilt axle (axis 4) for cross-comparison with the linear potentiometer to better determine the forces being applied to the pen nib. The final design is pictured in Figure 18.

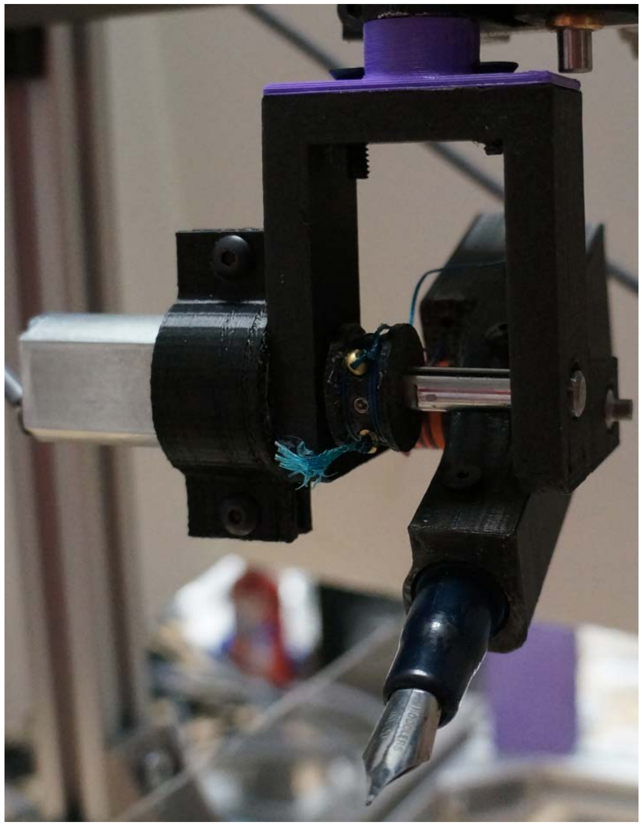

Figure 18: A picture of the pen holder end-effector. The entire body, bracket, and pulleys were 3D printed. The springs are connected to the pen by the blue cabling that goes around the middle pulley. The middle pulley is locked in sync with the pen holder. The bracket supports the axles on both sides to prevent bending.

GANTRY SYSTEM

A gantry table is a standard system for motion along the x-axis and y-axis used in many applications such as laser cutters and 3D printers. Since they are common, I was able to easily obtain parts. The majority were donated by igus's Young Engineers Support (YES) program. [23] The main concern with the gantry table was to make sure the desired motions were as smooth and free as possible and that there were no extraneous motions. These extraneous motions included any sort of twisting or bending that would reduce the smoothness of the linear motions and any sort of wobbling or shaking that would reduce the accuracy and precision of the position control of the pen nib.

The initial test was a prototype constructed on the body of a Printrbot Jr 3D printer (Figure 19). This was combined with the prototypes for the pen holder. The Printrbot's Repetier software was used to control this system. It proved that the pen could be moved about with a gantry system and draw lines. However, the axes of the Printrbot were not double supported which permitted a significant amount of play and was not very rigid. The belts were not tensioned well and would sometimes slip, which made the positioning highly inconsistent. The design for the actual gantry system was intended to avoid these problems.

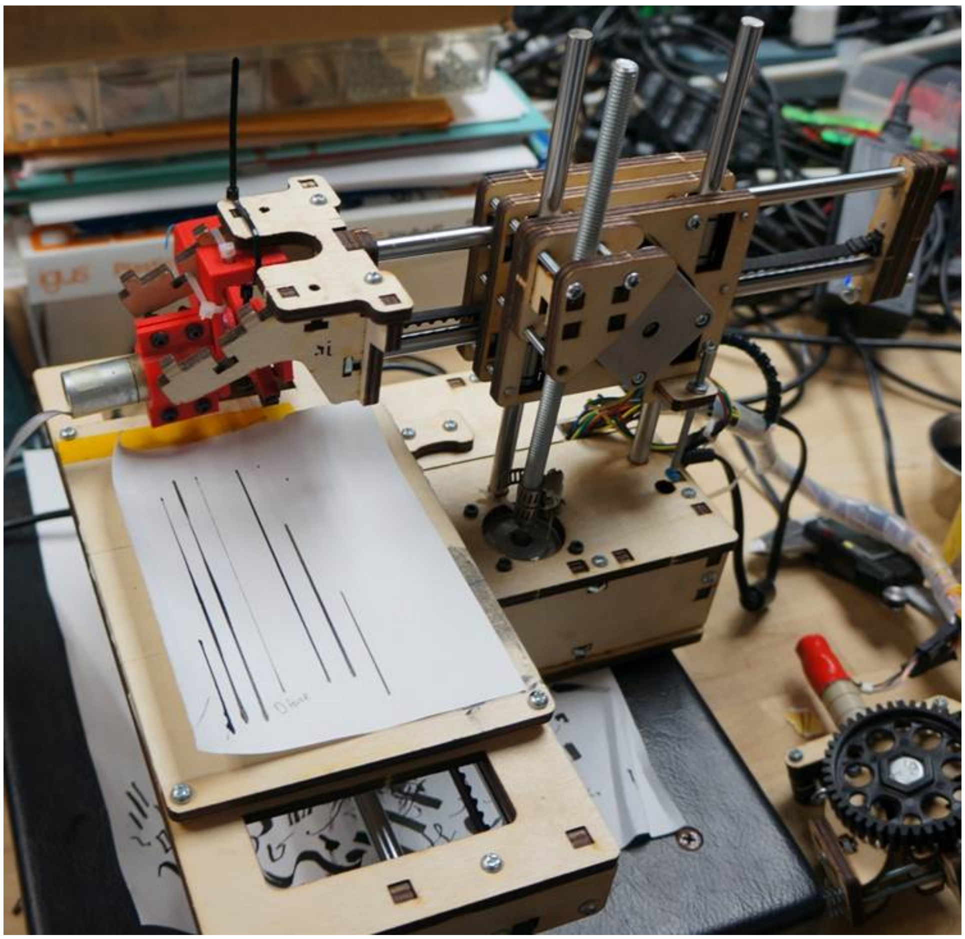

Figure 19: A prototype gantry made from a modified Printrbot Jr. The lack of double support for the rails and the loose belts created an unacceptable amount of play in the positioning.

My original gantry design had both the x-axis and y-axis mounted above the pen holder (Figure 20). However, this required both of the axes to be mounted perfectly flat in relation to each other and to the writing surface, which would have been difficult to assemble properly. Incorrect assembly could have caused twisting, wobbling, or other unwanted effects.

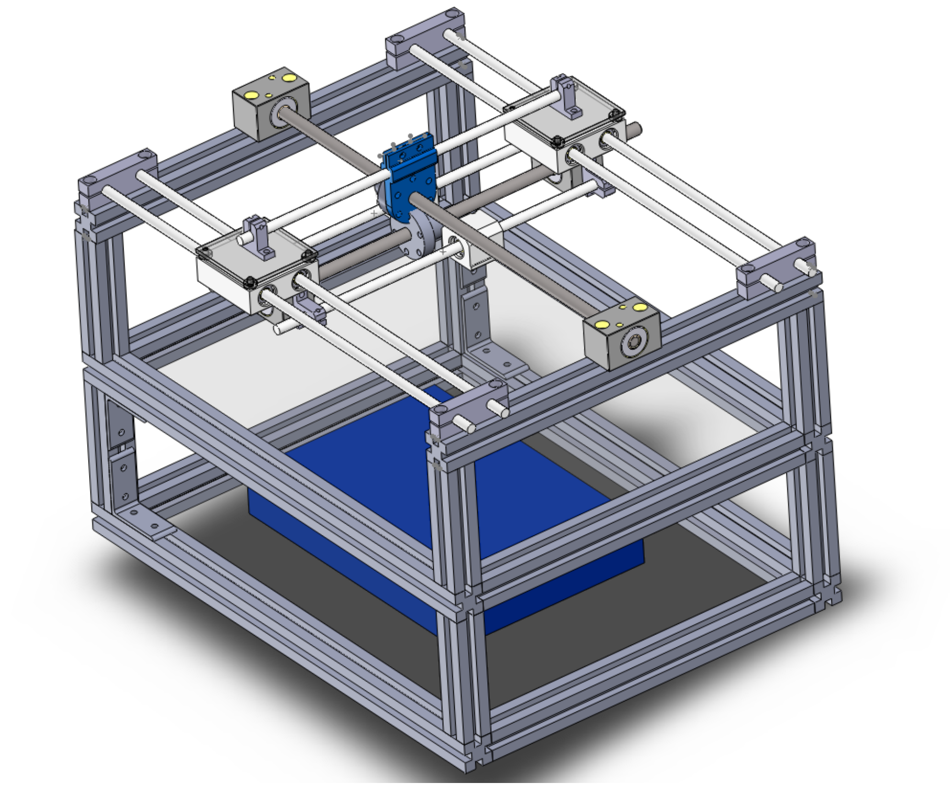

Figure 20: The initial gantry design with both axes mounted above the writing surface. The axes were double supported to help improve the precision and accuracy of the positioning. However, this design required that all four posts be perfectly level, and the rails perfectly parallel, which was infeasible.

I altered the design to have one sunken axis. The sunken axis did not require any support posts which increased its stability and rigidity. I could not make both axes sunken because the pen had to be mounted above the writing surface, so it could be pointed down in order for the ink to flow properly to the pen nib. To help prevent any twisting of the axes, both are driven in the center of two linear rails. I also chose longer linear bearings for the same reason. The longer x-axis is a lead screw drive and the y-axis is a pre-assembled belt drive based on the recommendations of an igus representative, to best fit the speed and mounting requirements and what they had available within reasonable lead times. This final design is shown in Figure 21.

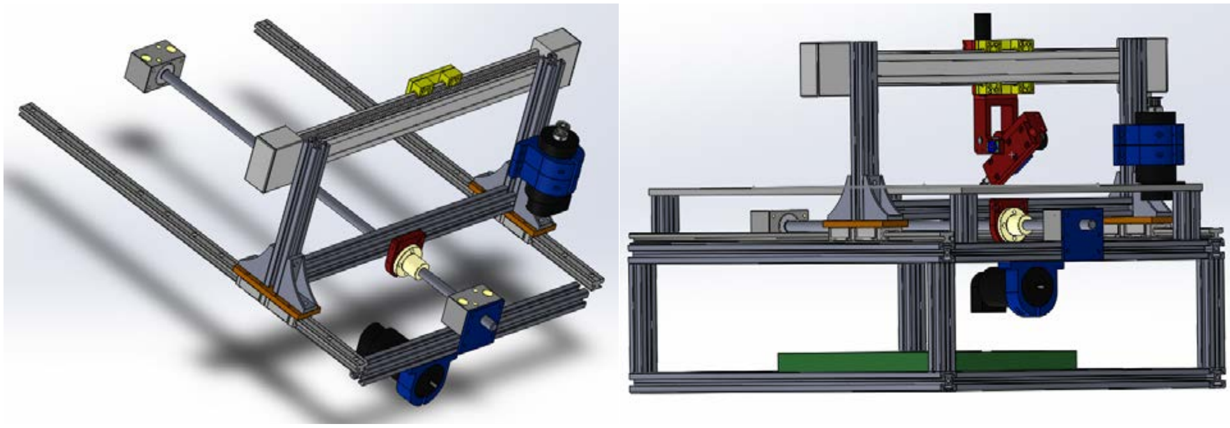

Figure 21: [LEFT] The figure shows the CAD model of just the elements that belong to the 2-axis gantry system. The lower axis is a screw-drive connected to linear bearings that slide on rails. Attached to each of the bearings is a post that supports the belt drive. [RIGHT] The full assembly. Note how the screw drive is sunken beneath the writing surface for greater stability and rigidity.

MOTOR SELECTION

After the mechanical design was established, I chose motors to drive each axis. To choose the motors, I used equations outlined by the textbook The Selection of High-Precision Motor Drives. [24] I needed to calculate 2 desired values to select motors: the speed of rotation in rpm and the output torque in Nm. A study on ballpoint pens estimated that the typical writing speed is 10cm/s. I added a safety factor of 2, and made the desired maximum velocity 20cm/s. [25] I also added a safety margin to the estimates of the weight each drive would move. I estimated the end-effector and rotation joint would weigh about 1lb, and used 2lbs in my calculations. With the posts and belt drive, I estimated the screw drive would need to move about 3.5lbs, and used 5lbs in the calculations for the lead screw. These safety margins ensured that the motors would never be pushed to their limits during operation.

The lead screw drive had an additional variable beyond speed and torque that provided more flexibility in motor selection. Igus offered two values for the pitch of the screw. I calculated two possible configurations that were dependent on the thread pitch (Figure 22). I gave both these configurations to a representative from Maxon Motors who found a motor that matched one set of values. I then acquired the lead screw with the necessary pitch from igus.

To choose a motor for the linear screw drive:

speed of rotation: $n_{in} = \frac{60}{p} \cdot V_{out}$

torque: $M_{in} = \frac{p}{2\pi} \cdot \frac{F_{out}}{\eta}$

where

p = thread pitch

η = total efficiency $\cong$ 35%

based on textbook's recommendation

Desired max velocity $\cong$ 50cm/s

p = 2mm	p = 4mm
$n = \frac{60}{2mm} \cdot (200\,mm/s)$	$n = \frac{60}{2mm} \cdot (200\,mm/s)$
n = 6000rpm	n = 3000 rpm

} speed of rotation

Approximate mass to move w/ safety factor = 5lb

Desired max acceleration $\cong$ 200 mm/s^2

p=2mm

$$\frac{2mm}{2\pi} \cdot \frac{(5lb)(200\,mm/s^2)}{.35} = .22Nm$$

p=4mm

$$\frac{4mm}{2\pi} \cdot \frac{(5lb)(200\,mm/s^2)}{.35} = .44Nm$$

} torque

Figure 22: The math for the motor selection for the lead screw drive. The value pairs were provided to the motor supplier, and the screw pitch was chosen based on the motors available.

The same process was repeated for the belt drive. However, the belt drive required slightly different equations, since it did not have pitch, but did have two pulleys with diameters “d1”. The force output required the weight of the end effector, but also enough force to overcome the initial resistance of the belt drive. The relevant equations and results are shown below. (Figure 23)

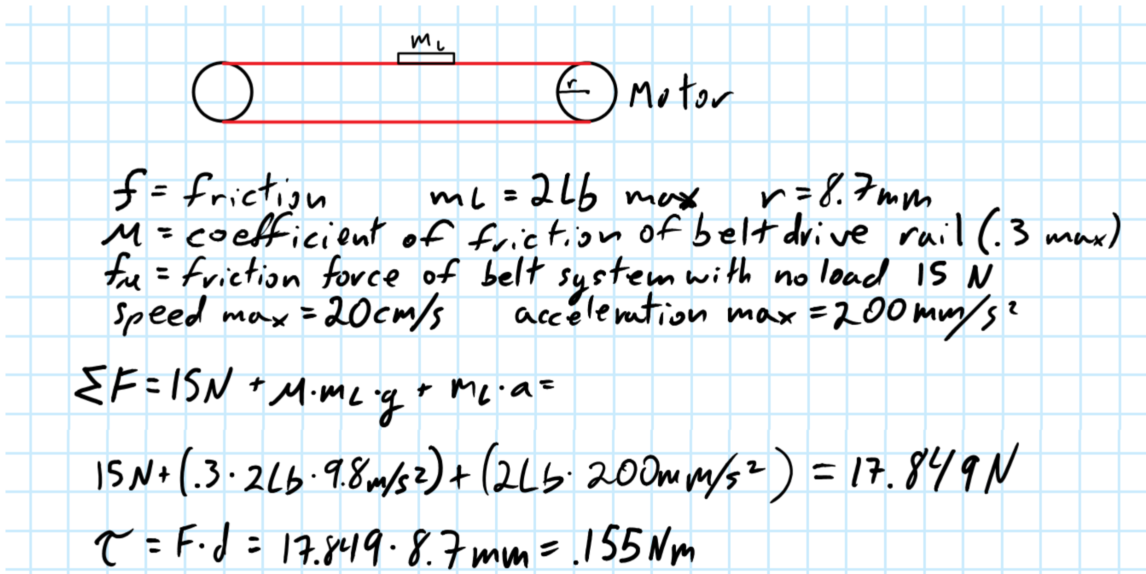

Figure 23: The math for the motor selection for the belt drive. The value pairs were presented to the motor supplier and the choice was made on their recommendation.

The other motors were more straightforward to choose, since they were connected to standard rotational axles with ordinary torque equations. The final values for all four motors (one for each axis of motion) are listed below in Table 1.

Axis	Rotation Speed 1 (rpm)	Torque 1 (Nm)	Rotation Speed 2 (rpm)	Torque 2 (Nm)
Pen	n/a	.3172	-	-
Screw	6000	.22	3000	.44
Belt	6000	.09	3000	.177
Rotation	n/a	.5	-	-

Table 1: The calculated desired values of speed of rotation and torque for each of the 4 motors.

For the PVT controller, the three positional motors (axes 1, 2, and 3) were all purchased with encoders attached. However, this will be described in more detail in the Control Architecture section. The positional motors were all connected to their drives by timing belts because these were available in the lab. Their use simplified the mounting process because the motors could be offset from the axis, which made the design more compact. The motors were clamped into place with 3D printed brackets that used a screw to tighten the clamp securely around the motor. The screw was threaded through a heat-inserted thread which was more secure than the 3D printed material. Since each screw only needed a single insert, there was no difficulty with aligning the inserts unlike with the pen holder. The offset, timing belts, and clamps for each of the 3 positional motors can be seen below in Figure 24.

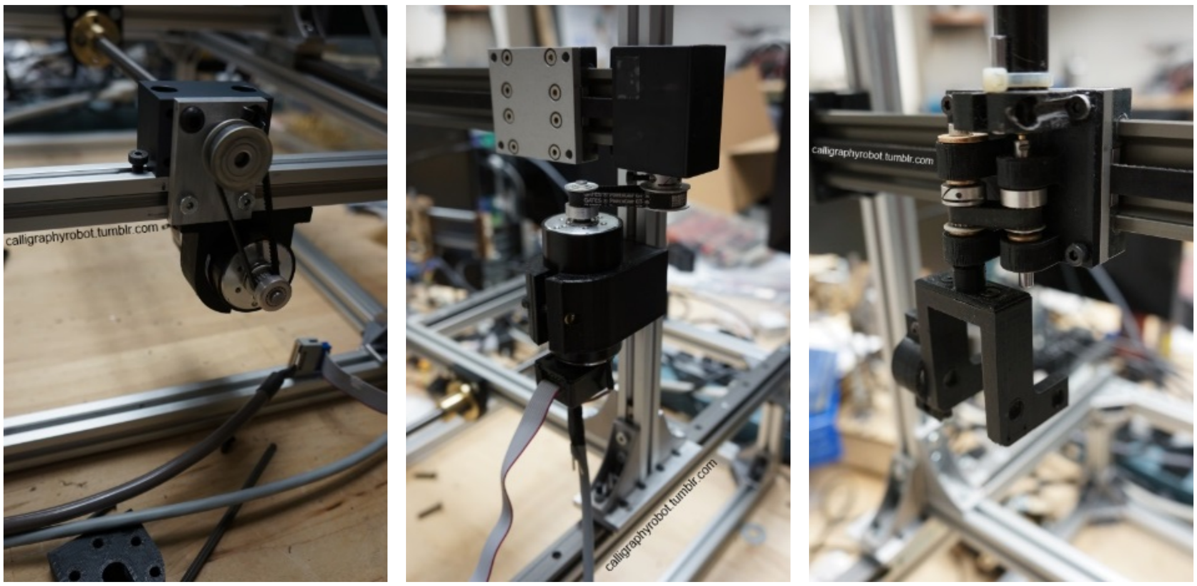

Figure 24: From left to right: the screw drive motor, the belt drive motor, and the rotation joint motor (with pen holder mounting bracket). All 3 are mounted with 3D printed clamps and connected to their axis via timing belts.

ELECTRICAL SYSTEM

Figure 25 illustrates an overview of the full electrical architecture of the robot. In this platform, The Intel DE2i-150 computer is the main processing unit. For writing calligraphic texts, the DE2i-150 would take in a desired text file and generated the appropriate motion plans which are output to a CSV file. However, the current implementation takes in raw Bezier curves which are converted to CSV. Then the CSV file is used to command the motion of all the different axes. All of these sensors communicate to the DE2i-150 over USB/FTDI. The pen holder rotation is controlled using an Ardunio Uno communicating at 1 kHz with the DE2i-150. The Arduino is fed vector velocity information and desired pen pressure; it then determines the desired motor power output based on a feed-forward controller with a PD control loop. The original goal was to utilize the onboard FPGA to perform this task but time constraints did not allow for that. The Maxon motors are set up in interpolated position mode; the controllers take in PVT values and create spline interpolations. The first motor in the chain is connected to the DE2i-150 computer via USB and then a CAN system is utilized to communicate with the rest of the controllers and synchronize the PVT movements.

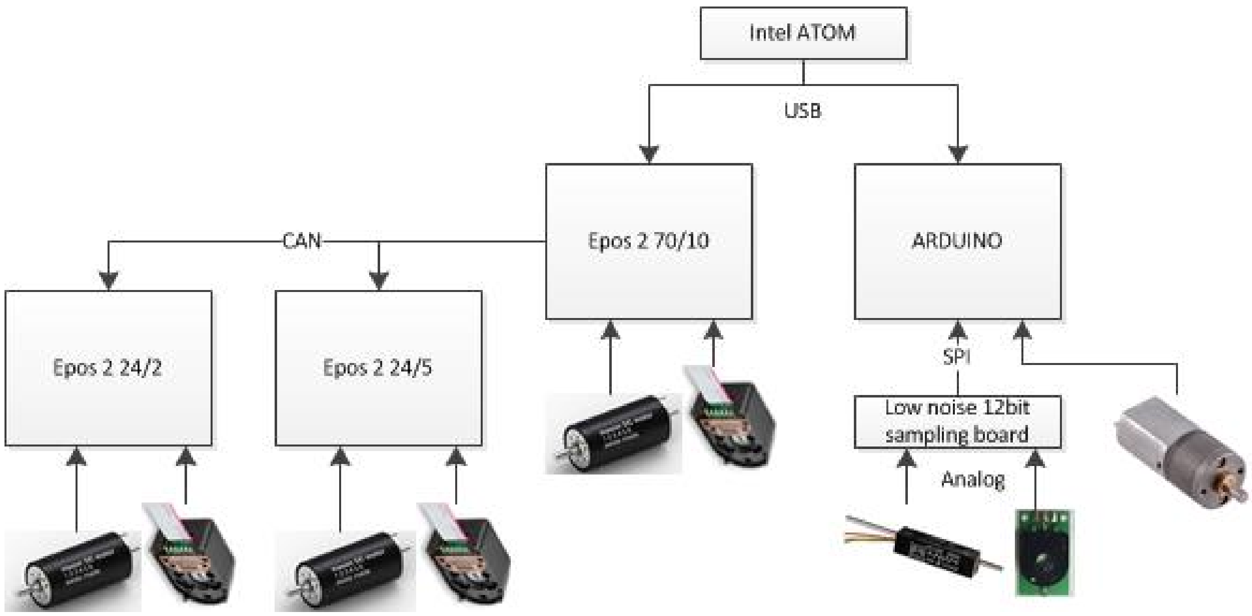

Figure 25: The image shows the layout of the electrical system for the robot. The left side is the positioning system and the right side is the force sensing system. This architecture is designed to make the two sides work cooperatively and simultaneously.

Control Architecture

For this project one of the main goals was to create a system able to generate smooth motions. Two motion control methods were studied for this project: linear path interpolation and spline interpolation via the use of interpolated position controller.

Most gantry systems, such as CNC mills, 3d printers, laser cutters, and CNC routers, use linear path interpolation with basic arc and circle methods in order to describe all the motions needed to generate any given motion path. These methods are widely used and have been adopted by many open source communities for home-made 3D printers and CNC mills, meaning they are simple to implement due to the extensive amount of documentation available. The linear path interpolation system also has very low overhead after the paths have been generated, reducing the computational requirements on the motion controllers. One of the main disadvantages of the system is its inability to make smooth curves and circles. It breaks curves into short linear segments that approximate a curve (Figure 26). For this system to represent a true curve, the system would need to break down all curves into a near infinite number of linear segments. The system limitations, communication speeds, and motion controller limit the number of linear segments that the system can discretize which makes it infeasible to use the common method of linear path interpolation. To achieve smooth motion paths, the project had to support the implementation of the more complicated method of spline interpolation.

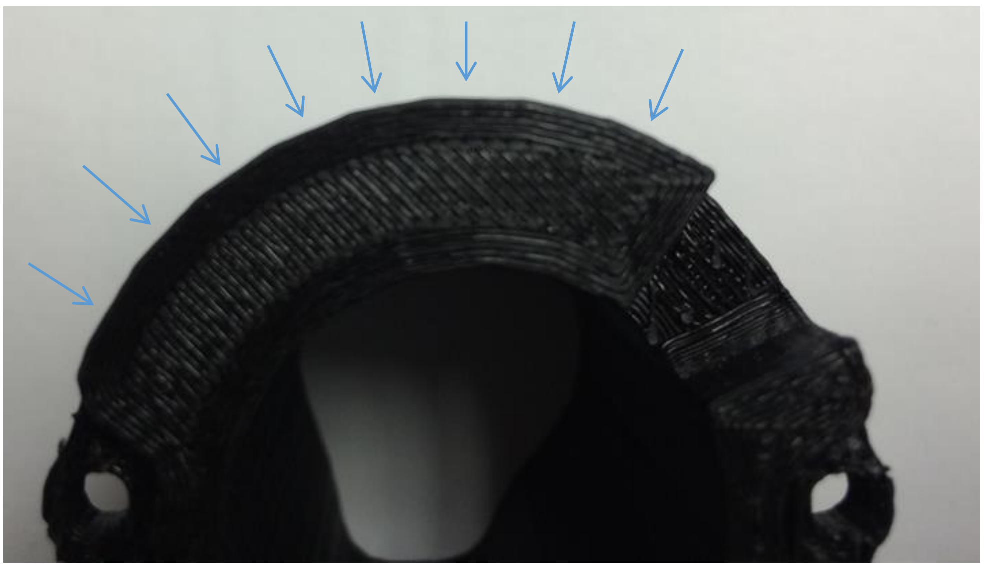

Figure 26: The image shows an example of a linear interpolation of a curve from a 3D printer. The arrows show the flat lines that make up an approximate curve rather than being a true curve. The point of using a PVT controller for spline interpolation is to achieve a smooth curve rather than the segmented one pictured above.

Spline interpolation, also known as position velocity time (PVT), does not discretize curves into linear segments. Instead, it creates curved motions by controlling the acceleration, velocity, and end position of the end point. Most position curves can be broken down into and described as third order polynomials, with a second order velocity polynomial and first order acceleration (straight line). This can be seen in Figure 27 below.

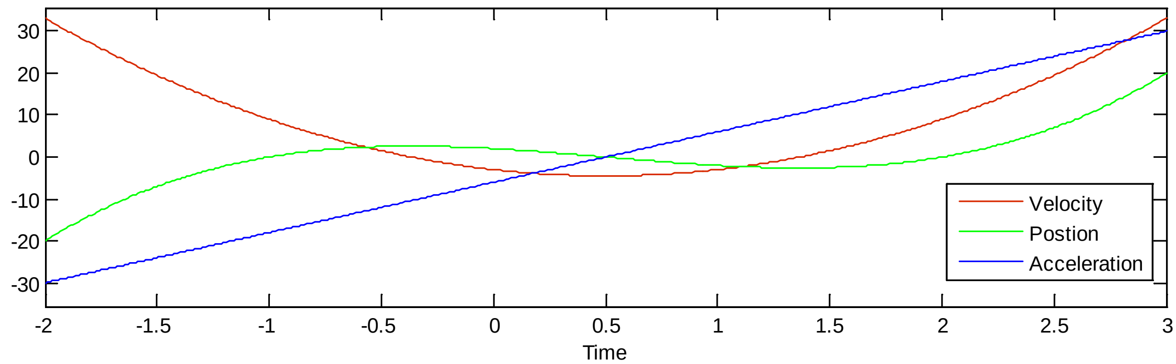

Figure 27: Relationship between third order polynomial (position), its derivative (velocity), and its double derivative (acceleration). These curves can be described by continuous polynomials which creates smooth motion rather than the segmented path from linear interpolation.

Therefore controlling a linear acceleration and following a desired velocity profile will generate a smooth position curve (Figure 28). An enormous benefit of PVT is the reduction in data transfer capabilities since the information for a given third-order polynomial can be described in a single PVT packet sent to the motion controllers as opposed to the information to describe many linear segments to describe a portion of an arc. In recent years, interpolated position through the use of PVT has become more widely used and a majority of high performance motor controllers have PVT built-in. An additional boon provided by PVT is the enforcement of continuity [26], or continuity of the velocity between curve segments. In current applications [26] having continuity produces significantly better results in surface finish for machining and better extrusion profiles for extrusion type 3D printers. For our application the continuity produces more even ink distribution in conjunction with the force control. The main downside is that it is still a newer, less used, motion planning system with a very limited amount of published information on how to generate PVT points from a large number of curves and how to synchronize the motion of the multiple axes.

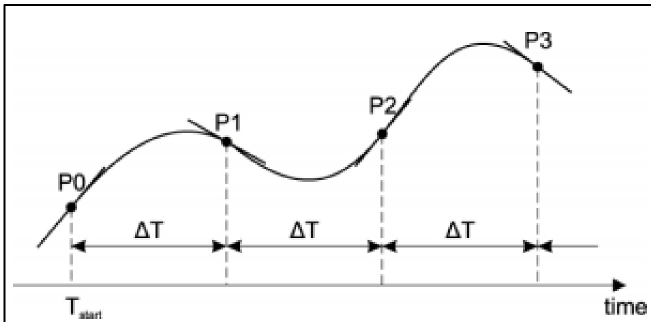

Figure 5-20 Interpolated Position Mode – PVT Principle

From two successive PVT reference points, the interpolation parameters a, b, c and d can be calculated:

```
d = P[t0] = P[n]
c = V[t0] = V[n]
b = T^-2[n+1] * (3 * (P[n+1] - P[n]) - T[n+1] * (V[n+1] + 2 * V[n]))
a = T^-3[n+1] * (-2 * (P[n+1] - P[n]) + T[n+1] * (V[n+1] + V[n]))
```

The interpolated values for position, velocity and (possibly also for) acceleration will be calculated as follows:

```
P(t) = a * (t - t0)^3 + b * (t - t0)^2 + c * (t - t0) + d
V(t) = 3a * (t - t0)^2 + 2b * (t - t0) + c
A(t) = 6a * (t - t0) + 2b
```

The calculation shows that it is not mandatory that the time intervals are identical.

Figure 28: An example from the documentation for the Maxon motor EPOS controller. It shows the smooth, continuous position curve that PVT control creates and relevant equations.

Bezier Curves

A common way of describing curves is through the use of Bezier curves. Bezier curves were popularized as a method to describe the curves of automobile bodies during their design process. [27] My project uses the Bezier curve to parametrically describe the position of the pen nib. Third degree Beziers were chosen due to the ubiquitous nature of software which operates can be used to generate them. The mathematical expression for a cubic Bezier is:

$$\boldsymbol{B}(\sigma) = (1-\sigma)^3\boldsymbol{P}_0 + 3(1-\sigma)^2\sigma\boldsymbol{P}_1 + 3(1-\sigma)\sigma^2\boldsymbol{P}_2 + \sigma^3\boldsymbol{P}_3$$

where $\boldsymbol{B}(\sigma)$ is the vector quantity describing all coordinates describe in each of the control points $\boldsymbol{P}_n$. The Bezier is defined on the parameter interval $0 \le \sigma \le 1$ such that the spline starts at $\boldsymbol{P}_0$ and ends at $\boldsymbol{P}_3$. The largest challenge presented by the use of cubic Beziers is that their arc length is not easily described as a function of the parameter σ. Arc length for a Bezier curve in 2D Cartesian space is given as follows:

$$s(b) = \int_0^b \sqrt{\left(\frac{dx}{d\sigma}\right)^2 + \left(\frac{dy}{d\sigma}\right)^2}\, d\sigma$$

which, for a cubic Bezier does not have a closed form solution. Arc length is important when mapping the position data to specified times and velocities. The arc length can be computed using a variety of numerical methods such as Riemann Sums or a Gaussian quadrature. To map a velocity profile to the Bezier path the velocity profile is integrated to a desired time resulting in a distance s. Next the distance s is used to find the parameter b_s which corresponds to the arc length $s(b)$ from the above arc length integral which is approximated using the aforementioned numerical methods. With the parameter the position information can be directly computed from the numerical expression for a cubic Bezier. The velocity can be calculated by taking the profile velocity at the evaluated time, $V(t)$, and decomposing it into vector components dictated by the angle of the tangent of the Bezier evaluated at b_s. Mathematically this can be expressed as:

$$v_x(b) = V(t)\cos\theta_t$$

$$v_y(b) = V(t)\sin\theta_t$$

$$\theta_t = \tan^{-1}\frac{B'_y(b_s)}{B'_x(b_s)}$$

With these three pieces of information calculated a PVT packet may be constructed and provided to the drives for interpolation.

RESULTS

The positional system was able to successfully draw Bezier curves that were provided as input. An example is shown below (Figure 29). This curve is slightly shaky because the force control system was not running at the same time; rather than pressing against the writing surface, the pen nib was free to bounce slightly across the surface of the paper,

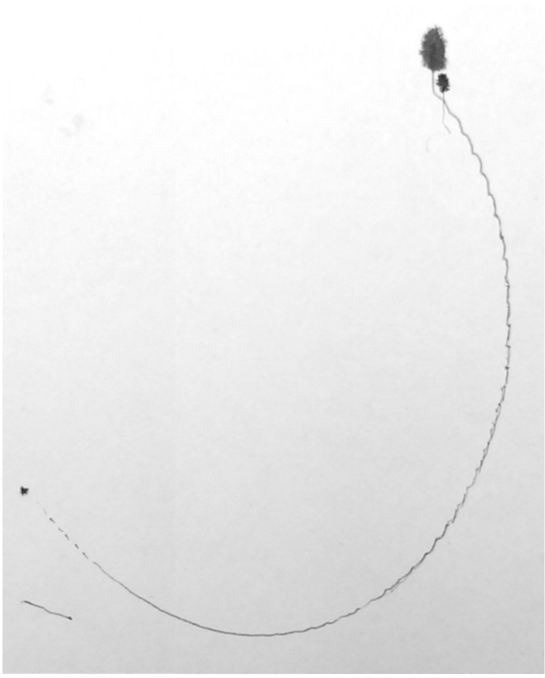

Figure 29: A curve that was drawn by the gantry system under PVT control. The curve is slightly shaky because the force control system was not running at the same time in this test.

The system was able to successfully control the force based on measurement of the SEA. Below is Figure 30 which shows the results of a simple test that I conducted with the force-sensing control. The desired force value was set to 1.5N and told to maintain that constant force.

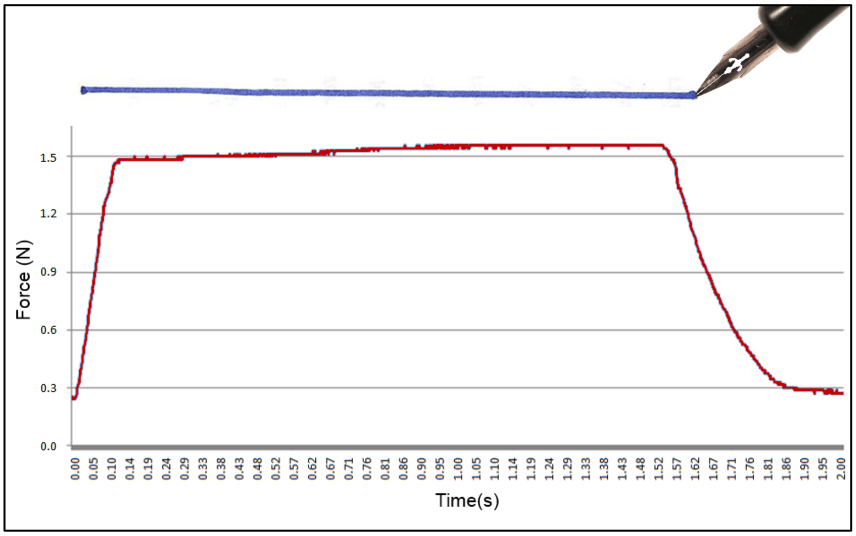

Figure 30: The top of the figure shows a line that was commanded to maintain a consistent force. The graph shows the measured force. The relatively flat plateau shows that the controller was successfully in maintaining a steady force. The slopes on either side show the pause where the pen was initially placed and lifted.

Due to an organizational error, there is not a copy of test results from the combined systems working together. At the time of the filing of this report, the robot has been partially dissembled for transport to the Cornell Cup Competition. However, the robot's design successfully met all the criteria laid out at the beginning of this project.

BUDGET & SPONSORS

I had a limited budget of $1660, courtesy of the Cornell Cup and WPI, for this project so I took advantage of sponsorships, student discounts, and promotions wherever possible. Speedball Art graciously agreed to donate ink and pens to the project that were used in initial testing and planning at the beginning of the project. Igus Inc has the Young Engineer Support (YES) program especially for providing free supplies to support student engineering projects. They contributed the parts for the two linear axes. I took advantage of a promotion from MiSumi that offered $150 of supplies free for first time purchasers to buy the aluminum extrusions for the frame, with corresponding corner brackets and nuts. Intel provided (and required the use of) their Intel Atom board as part of the competition.

My largest purchase was for motors from Maxon. Maxon is a competition sponsor and a local company representative offered the 3 positional motors, encoders, and controllers at a significant discount. I spent a majority of my budget on these items because they were absolutely crucial for the precision, accuracy, and smoothness of the positioning and motion system.

RECOMMENDATIONS AND NEXT STEPS

There are three main extensions or upgrades to this system that I would recommend: increasing the possible input, dynamically calibrating the force control, and a robust user interface.

The current input is limited to a series of specific Bezier curves. This is equivalent to the letters of a single, specific font. To make the robot more adaptable for different research purposes, it would be ideal to be able to take any black and white image, determine if it is feasible curve, and, if so, draw it. This would allow the robot to not just write letters, but draw lines – a necessary feature if the robot would be used to research automated surgical incisions. However, this would require a complex program that could identify certain limits such as not being able to draw wide lines upwards, cutting with a pushing motion, or how to handle intersecting lines and sharp turns. Unfortunately, the system requires extensive computation in converting Bezier curves to PVT. A more elegant algorithm with adaptive point generation based on curve complexity could greatly reduce computation and allow for more fonts or paths to be used.

I would also like to be able to add dynamic calibration to the end effector. Although the spring selection limits the end effector to a certain range of forces, not every end effector responds in an identical or linear manner to the application of force. A program that could test a new end effector and dynamically change the force and position control program to match its characteristics would make the robot much more adaptable.

The interface could also be vastly improved to allow users with low technical proficiency to operate the robot. An improved interface might consist of a touch screen display with built in help menus, usage tutorials, and demo operations. To fully realize this goal extensive user interface studies would need to be performed given that the novelty of this robot would require some intuitive operation method.

Conclusion

This report describes the design, assembly, and testing of a system that utilizes a cooperative position and force control system. A series elastic actuator introduces compliance to the end effector and a measurement for force sensing. A PVT controller with Bezier curve inputs uses polynomials to command a gantry table to create perfectly smooth and curved motion paths. This system's delicate-yet-stable force control and finely tuned position control has potential application for surgical tasks. This project was developed in part for the Cornell Cup Competition. As part of the competition, two design reviews were conducted during the design development process. A detailed analysis of the design review process, with generalization to help other students, is included in Appendix A.

NOMENCLATURE GLOSSARY

- DoF – Degree of freedom
- SEA – Series elastic actuator
- Flex nib – a pen nib that is flexible
- CAD – Computer Aided Design
- PVT – Position Velocity Time
- COTS – Commercial Off The Shelf. Parts that can be bought directly from a supplier.
- Bezier – Parametric curve used to model smooth curves
- PID – Proportional Integral Derivative
- Controls – The mechanism by which something is controlled, in this case the mathematical system by which we determine desired output power to motors based on position information collected from the different joints.
- SPI – Serial Peripheral Interface, bus communication protocol for low level microcontrollers to interface with different IC.

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APPENDIX A: DESIGN REVIEW CREATION PROCESS

Analysis of the Rhetorical Context and Choices

CONTENTS

Introduction: Design Review Creation Process

The Cornell Cup requires participants to adhere to a rigorous engineering process that models practices in engineering industries. Part of this process was submitting regular design reviews. Design reviews are a tool used to keep a project on track, maintain quality, and ensure the end result matches the initial requirements. Therefore they are a significant engineering tool. This appendix includes an analysis of the design reviews created for the Cornell Cup. Their creation, execution, and results are analyzed through experiential knowledge, an understanding of rhetorical and genre analysis, as well as commentary and advice from articles and other studies. The purpose is to develop a method of approach that helped the creation of design reviews and, more importantly, can help guide the decisions of future students made while crafting design reviews.

Studying or learning design reviews in the broad sense is a difficult task. They can be used in any case where a design is being developed, meaning they are used across a variety of industries. Companies often create, consciously or not, their own in-house method of the design review process. Since design reviews are so widely used and critical to industry success, many engineering programs at universities make some attempt to teach their students the basics of design reviews. However, these programs vary widely from school to school as professors adapt them for the academic environment. These variations can make it difficult for new-comers who must learn a new set of expectations. The ability to understand the demands, needs, and constraints which influence a design review, and how they influence, makes this task more feasible.

Rhetorical and genre analysis are methods of asking about the context and purposes surrounding a type of communication. This study expands upon more general frameworks for approaching document creation by creating, reflecting, and analyzing the creation and results of several design reviews over the course of this project's development. The study explores who the stakeholders were, the purposes of the review, what information was included in the review and what was left out, and how the information was presented. The exploration highlights the decisions that were made during the creation of the design review presentation and how the decisions affected the reception, comprehension, and reaction of the review. Exploring these relationships demonstrated how analysis frameworks can be applied and how they work in practice. This demonstration develops a clearer picture of what questions and choices are present when approaching a design review.

There were three design reviews required as part of the Cornell Cup which are described further in the Background. The Methodology section outlines how rhetorical and genre analysis, experiential knowledge, and outside commentary will be utilized in the analysis of these design reviews. The creation of each design review is analyzed with subsequent results and conclusions from each. This outline will help other students who wish to approach their design reviews in a more conscious manner.

Background & Literature Review

Design reviews are a commonly used tool in disciplines that create technical designs (as opposed to artistic). To understand the purpose and approach of this study, it is more useful to first explain in greater detail what design reviews are, their general purposes and uses in the sense of why they matter and are important, what their role in the Cornell Cup competition is, and the assumptions and expectations present at the beginning of this study. This background should help to ground the study in some foundation as well as justify why this exploration is important in the larger conversation regarding the creation of design reviews.

WHAT ARE DESIGN REVIEWS?

A design review is a meeting that can be held in-person or virtually where relevant stakeholders discuss artifacts produced during the design process. Information can be transmitted orally, visually, and/or lexically by way of notes, documents, models, simulations, images, videos, and conversations. Reviewers examine these artifacts prior to the meeting; at the meeting they question and offer feedback in order to improve the design. Reviews are usually held iteratively during development as the design matures.

In modern industry, product development tends to be split across multiple departments, sometimes across companies. Sales and/or Marketing may identify a new market opportunity or be contacted by a potential customer and they dictate the requirements the product must satisfy. Finance controls the budget for the process. Mechanical, electrical, and software teams need to work together to build an integrated solution, and their design depends in part on feedback from industrial designers and representatives from manufacturing. If the industry is highly regulated – like defense, medicine, or food – health and safety representatives will also need to be involved. In a smaller start-up, some employees may be playing multiple roles, filling in as needed. Given so many contributors and other possible stakeholders, a formal process was developed by managers to help this process run smoothly and reach a successful end project.

Design reviews are a commonly used tool in the formalized processes of development. They require everyone who is critically involved in the project to take time to reflect on what has happened so far, what still needs to happen, if they are on track to meet the initial requirements, and if everyone is on the same page and agrees on what their goals are. When it functions as intended, it prevents employees from working at cross-purposes, keeps them focused and engaged, uncovers potentially costly mistakes before there is a commitment to production, and generally keeps the business running smoothly. The design review can also be used as a hard stop where development cannot move forward unless certain expectations and criteria have been fully satisfied in the review.

Why Cornell Cup Requires Design Reviews

The competition asks students to develop an engineering project while adhering to industry practices such as timelines, budgeting, and reviews.

> [A]t some point in your career, sheer skill and talent will not be enough alone to realize your vision. You need to develop a plan and ways to formalize your thoughts so that a team of people can work efficiently and effectively together and hence allow you to focus all of your skills and talents in one area at a time while helping to ensuring success for your overall project… This competition will help push you to excel in developing new ways of thinking to take from being a student into becoming a high achieving professional. (Cornell Cup, Student Info)

The Cornell Cup provides a specific situation which demands the application and development of knowledge that is required across a broad range of technical careers. Engineers traditionally are not strongly concerned with their communication skills. Tying the need for these skills to a challenging engineering competition provides motivation and context for students to learn them.

Although engineering ostensibly has no relationship with writing, communication skills are critical even in technical fields. "[L]arge numbers of people write, are even compelled to write… they fill out forms, compose memos or reports, send interoffice emails" (Guillory 112). These daily communication tasks are crucial to the day-to-day functioning of an office. Beyond these, skills in technical writing are even more necessary. "An ever increasing dependence upon reports, arising from more and more specialization within engineering organizations … The quality of reports should now measure up to the importance attached to them" (Durkee 348). Studies of the Challenger disaster blamed, in part, an unpersuasive PowerPoint presentation (Guillory 121). A study of memos involved in the Three Mile Island incident noted engineers' assumed their recommendations were implied (Guillory 131). These examples show that failures of clear, coherent communication can contribute to extreme results and highlight the need for all engineers' to develop their professional communication skills.

IMPORTANCE OF DESIGN REVIEWS

Given this background, it is a reasonable assumption that productively contributing to design reviews is a crucial skill that technical students should develop. However, it can be difficult to find reference materials, such as examples or instructions, which are neither too general nor too specific to learn about the subject and its application but in generic, overall form. Documents that are available tend to fall into the extremes of either very specific case studies that are dependent on the specific field, the number of people involved, or the departmental setup, and anecdotes or very abstract level discussions that attempt to account for all forms of design review-type activities within the context of all development processes (Huet "Making Sense", Nam Le et al, Nihitila, Huet "Communication"). Attempts to review this literature found significant breadth and variety in the forms of design reviews. Furthermore, there were no documents specifically pertaining to robotics engineering, which may be explained by the fact that robotics engineering is a relatively new field and most companies are likely to divide it into traditional mechanical, electrical, and software engineering departments. This complicates any pursuit to require a useful and general knowledge.

Despite this breadth and variety, there are general similarities, common themes and messages, and trends that wind through the documents. If it is possible to overcome the difficulties with finding an appropriate corpus of work to analyze, this knowledge acquired from analysis of it can be transferred to other similar domains:

> The variety of format in industry and business is so vast that [a student] cannot expect training to cope with the details of each, but that an ability to deal with the principles of technical presentation gained from careful work with any one format will enable him to handle any other he may later be required to use (Childs 395).

By identifying the complications involved in finding useful and applicable generalities, these can be appropriately addressed and compensated for during the genre analysis.

One complication is that the design review can be trying to fulfill any number of a huge range of purposes. Some of these purposes include maintaining compliance with requirements, assessing progress, exchanging information, facilitating collaboration, saving cost, preventing errors, justifying decisions, learning from collective experience, and developing greater collective experience (Craig; Huet, Culley, McMahon, Fortin; Carlin; East, Kirby, Perez; Beiter, Ishii, Karandikar; East, Roessler, Lustig). Modern business documents developed for the purpose to "relay communications back and forth between the top and bottom of the organization or laterally between departments" (Guillory 116). However, depending on the level of specialization and stratification of the management hierarchy of the business, the size of the project, and the level of oversight, there are many variables that influence what communication is being relayed to whom. This inherently creates a great diversity in the purposes that the communication is trying to achieve, which can be very difficult to parse into useful axioms.

The design review is a standard project management tool that is used across a wide variety of industries from aerospace, to defense, manufacturing, architecture, infrastructure, medical, and domestic products. These industries all have their own norms, traditions, and best practices that will influence their expectations of any communication. Specifically in terms of design reviews, there are enumerable variations; most companies have their own names, templates, and preferences for design reviews. For example, a company that only has two design reviews may have a "preliminary design review" and a "critical design review", others may have a requirements review, preliminary, critical, and prototype reviews, still others may just have multiple design phase checks or development reviews. ("Design Review" is used in this report as it is the term utilized by the Cornell Cup competition.) The size of the project will affect the number of reviews, both in terms of project length and number of stakeholders involved. However, by finding relationships between these variables, it is possible to find advice that can be generally applicable.

In order to cope with the varieties, a diligent study should uncover the general but applicable trends and approaches that are useful to a student new to the design review process. These trends and approaches should include principles to follow to analyze the rhetorical situation and methods of self-reflection regarding the project, so that the student may develop the "ability to deal with the principles of technical presentation" in order to "enable him to handle any other he may later be required to use" (Childs 395).

PRIOR KNOWLEDGE

Coming into this project, I had expectations that came from my own prior experiences with design review activities and research into other studies and conversations regarding design reviews. These impressions and expectations played a large role in the questions asked and choices made during the creation of the first design review.

As an engineering student at Worcester Polytechnic Institute, I was required to take part in several design review activities for different classes. These classes included Introduction to Robotics Engineering (RBE 1001), Unified Robotics I-II (RBE 2001, RBE 2002), Software Engineering (CS 3733) and Kinematics of Mechanisms (ME 3310). These design reviews tended to be highly informal. Depending on the project, either one or two design reviews were required. The first (or singular) design review acted as a reality check and a deadline. Students were asked to brainstorm a few concepts, draw up some sketches, and make some basic evaluations of these designs in order to narrow it down to one or two. The sketches would be shown at the actual meeting, with the concepts and evaluation process conveyed verbally. The professor would give a few comments regarding the design – usually acknowledgements for gaps that had not been considered, cautions regarding feasibility and practicality, suggestions for possible improvements, or concrete advice on how to actualize the concept. If there was a second design review required, it would be similarly informal and focus more on concrete plans for actualization in terms of supplies, connections, space allotment, and/or system architecture. While these design reviews were clearly a highly stripped down version of anything engineering students could expect to see in professional industry, they did teach the basic purposes of design reviews.

The classroom design reviews were based upon the importance of plans. They taught that engineers must have a plan before beginning to build anything. These plans are necessary to improve a project's feasibility, because there are many needs, demands, influences, and requirements that affect any design. For example, any design must work within the physical laws of nature, considering forces, thermodynamics, kinematics, signal speeds, and so on. These physical limits were the most basic requirements. Other factors such as efficiency, novelty, cost, size, weight, ease of build, ease of maintenance, time required, and ability to obtain the desired parts also had to be considered. Some could be considered negligible, and others varied in priority. These priorities varied depending on the project and surrounding situation. The surrounding situation could include other influencing social factors such as professors' preferences and intent or group members' experience and knowledge, and group cohesiveness. Attempting to design a solution without thinking about these influences would almost guarantee the solution would fail in some way – either mechanically or to satisfy the individuals who held a stake in its creation. It was conveyed that this same environment would exist in industry, even if the factors and priorities may change. Creating a plan forces the designers to balance the factors and make choices rationally so that their end product would better align with their end goal.

The design review became an important part of the plan due to human limitations. The design review in this classroom environment became a vehicle for the professor to offer advice and further teachings, as well as a way for the professor to judge progress, develop a baseline to compare the final project to, and a method to spur on procrastinating students. As students, we did not have the technical or experiential knowledge that our professors had acquired. It was quite possible we would make inaccurate assumptions regarding practicality or feasibility or forget to consider a factor that could critically affect the design. While this is especially typical of students, it does not fully go away in the profession. Different engineers have different areas of specialty. Humans are prone to make mistakes or forget. Expansive projects that require coordinating components can have a complex web of requirements that are almost impossible to consider fully in the first try. Knowledgeable advice and more eyes can improve upon a design or uncover overlooked factors. A stronger, more comprehensive design should avoid more errors and problems during the actualization of the design. In this way, the classroom design reviews did provide a basic introduction to the most fundamental purposes of design reviews and provided foundational background knowledge. However, there were limits to the experiential knowledge gained from the design reviews.

These classroom design reviews were created in an artificial environment that did not fully replicate professional engineering. For example, these design reviews were not concerned with the mechanics of how to present a design review or what should be presented other than *something* pertaining to the design. The purposes of both the authors and the reviewers are different between the classroom and in industry. The professors who were acting as the reviewers did not look for comprehensiveness or thoroughness in addressing the factors, so long as several were acknowledged. The format of presentation was highly unstructured; a few sketches might have been brought to the meeting and the rest of the information was conveyed orally. There was no expectation of PowerPoint slides, tables, figures, charts, graphs, CAD illustrations, or mathematical analysis. The design review meetings tended to be very short as well, only 5-15 minutes for the full “presentation”. Beyond the mode and contents of the design review, the context, and therefore the purposes, of the design review were different than what I believe they would be for a professional one. The design reviews factored into our, the authors, project grades which often shifted the primary focus of the design review from soliciting useful feedback to appeasing what we believed the professor wanted. The engineering projects were low stake; they were built over the course of only 2-4 weeks, and once assigned a grade the project would not be produced, marketed, or used by others. This meant that the short final demonstration was the end-all be-all, and factors such as durability, cost, user-friendliness, aesthetics, safety, and maintenance were often ignored entirely.

However, the classroom is not as entirely artificial as may be supposed. Classroom assignments may be accused as demonstrating learning rather than acting to accomplish a practical purpose. This accusation holds less weight for design-review based activities. The professor in this case holds a power of authority similar to a boss or customer may hold in a professional design review. Students' worries about earning a grade are similar to engineers' worries of making a sale or earning a good performance review. Nor is there the artificiality that comes from writing or speaking for a fictional and hypothetical audience. The classroom design reviews are made for an actual engineering design, the professors have genuine knowledge on the subject, and do have a stake in providing a legitimate review and feedback to the students. The differences between classroom and professional design reviews appear to stem more from the impoverished environment of the classroom environment as outlined above: less time, less concerns, less forward-thinking, etc. A competitive environment, such as the Cornell Cup, helps to enrich this environment somewhat and makes it closer to a professional environment.

The Cornell Cup does provide a more complex and rich environment for the creation of design reviews, although it still does not fully replicate a professional engineering situation. Like the class projects, the Cornell Cup asks for small groups of 3-5 students. While a team this size might occur in start-ups, large engineering companies may have project teams with significantly more members that may belong to multiple departments. The competition does have an optional Entrepreneurship component that asks for the project to be developed as if it were being intended for production. However, due to time and resource constraints and the nature of my project, I did not focus on these concerns. My project advisor was a professor who was assigning a grade to my work, making the dynamic different than a boss to an employee. Yet the Cornell Cup did bring in the added complexities of caring about the content, method, and style of the design review by requiring each one to be graded on a rubric they had created. The competition also brought in more factors than the classroom projects such as budgeting, a longer development period, and the need to impress judges who were not in control of my grades. This more complex situation was such that it could be informed by my prior knowledge but provided opportunities for further learning and analysis. In order to study the Cornell Cup design reviews in a manner that could be more generally understood or applied, I supplemented my experiential knowledge by researching other articles and studies of design reviews within a professional business setting.

To gain a better understanding of how design reviews are talked about, I found articles and studies that considered design reviews from many different viewpoints. One type of approach was advice from engineers, who had gone through multiple design review processes, informing their fellow engineers what lessons they have learned and how to make a design review more effective (Craig, Carlin). Their advice focused on how critical thorough preparation is for design reviews with details on how and what to prepare as well as how critical attitude is to the process. The conversation regarding attitude reflected how important the social dynamics of the presenters and reviewers are: using the design review as a way to show superiority or "score points" was condemned as one of the easiest ways to make the design review process irrelevant to constructive progress. Other articles were communication studies that tracked what information was shared, how it was shared, how it was documented and recorded, and how well the final archives matched the initial information (Huet "Communication", Nihtilia). They identified that the types of communication used in design reviews were to inform, justify, persuade, or a future action step (Huet, "Making Sense").

While I did not find enough of any one kind of these articles to provide a comprehensive basis for analysis, together they furthered my knowledge of what design reviews are and can be. Collectively they also addressed, at least partially, all of the factors that became important for rhetorical analysis. The articles created a much more complex picture of design reviews, especially in terms of the people and purposes that could influence the design review. The studied design reviews occurred in different industries, companies of various sizes, projects with different scopes, and varied in many other ways. These variables highlighted many of the different factors that could influence how a design review manifested:

- Bosses, engineers (potentially from multiple departments or specialties), customers, marketing and sales departments, and governmental agencies could all have different intents and desires for the design review.
- These different parties could be presenting or advising the design review. These different roles could shift what and how the information was presented.
- The design reviews could be used to justify, inform, explain, persuade, question, decide, or criticize based on the interactions and relations between the desires of the presenters, the desires of the reviewers, and what decisions had been made or needed to be made.
- Design reviews could utilize different formats of presentation, including oral meetings, slideshows, or virtual meetings.

These factors were a complicated, interconnected web of influences. They were difficult to pull apart into clear cause-effect relationships that could guide the creation of a design review. However, for the sake of attempting to understand the process better, I attempted to partially isolate some of the different groupings or species of influences and factors:

- Stakeholders: Individuals that are invested in outcomes of the design review for some reason.
- Purposes: Actions the design review must fulfill at a basic, technical level.
- Pressures: External exigencies that are generally created by the stakeholders but go beyond the more basic requirements of the purposes.
- Features: The type of information included within the design review, especially in the sense of what information is available and what demands the type of information makes on the mode of presentation.
- Documents: The different possibilities and limitations of how the information can be presented.

This model provided a grounding to understand my experience of creating the design reviews and provides a way to organize the discussion regarding the design review. The relationships between these components were not a straight forward hierarchy, but a series of influences that interacted with each other and demanded some sort of balance between them. After I completed the first design review, I was able to refine this model further which will be shown at the end of the analysis of the first design review.

METHODOLOGY OVERVIEW

Forms of writing are defined by certain influences and results. While these tend to be picked up tacitly by writers to some extent, an informed and self-aware approach can produce documents of better quality. This study examines two design reviews created as part of the Cornell Cup competition. The presentations of each review were filmed for analysis. By reflecting on and critically analyzing the creation process and presentations , including rhetorical influences, genre analysis, and articles regarding design reviews, this study will be able to recommend a method that others can use to approach the creation of design reviews in an informed manner.

Method of Analysis

The goal of this study is to use the rhetorical frameworks and guidelines of various sources to explore and be able to articulate the larger contextual forces that influence the design review. The forces include purposes and uses as well as stakeholders and constraints. The research that formed part of the background knowledge for this study revealed that there were significant variations within design reviews to the extent that “design review” may possibly be better considered as a metagenre that contains more cohesive subgenres (Bean). Yet a metagenre is still a recurring situation that has certain kinds of contexts in play.

Genre analysis is the act of examining instances from a body of media to find insight into what a consistent form of rhetoric is doing, for whom, and for what purpose try to establish if the works belong to the same genre. “The term genre refers to recurring types of writing identifiable by distinctive features of structure, style, document design, approach to subject matter, or other markers” (Bean), or, in other words, genre is “a sociopsychological category which we use to recognize and construct typified actions within typified situations” (Shaping Written Knowledge). A genre analysis allows a writer to better understand and position themselves in regards to the examined body of media.

Genre is a conceptualization of a definition that is fluid and often approximate. Genre can be defined by many traits in addition to “structure, style, document design, [and] approach”. Participants who create and respond to the body of work can define the genre, as well as the purpose of the works, the effect the works have, and "the environment of its production and reception, including its historical and cultural association" (Shaping Written Knowledge). Writers both work within and shape a genre. However, this process, especially in engineering fields, is often done tacitly where the writer is not self-aware of the features of the genre or how the features arise from explicit and unspoken purposes, contexts, etc.

Design reviews do not lend themselves well to a full genre analysis. During the research for the background and literature review for this project, I came across a number of different styles of design reviews. The types and amount of information contained, how it is presented, when it occurs, and who is involved seems to vary for nearly every review. Different industries, companies, even departments have their own expectations regarding design reviews. Furthermore, many design reviews are produced as internal company documents and can consist of multiple documents of different formats, which made it hard to find a thorough set of examples to analyze. Genre itself is a fluid understanding as the quantity and similarity of genre characteristics which define a "prototypical" member (Bean) are always under debate (Shaping Written Knowledge). These two sources of uncertainty and variety would make for a very large and complex scope to the point of being unmanageable. However, this does not mean that genre analysis is not a useful tool for this study. Through my analysis, I try to define the contextual pressures and/or characteristics of the design review as a broader type of genre that can utilize many different types of documents.

Analyzing genre is an "interpretive, constructive tool" (Bean). Referencing and incorporating some of the approaches of genre analysis in this study will facilitate a better understanding of the interaction between the rhetorical situation of the design review and the created product. An awareness of genre contributes to understanding "expectations, possibilities, limits and constraints" of design reviews (Bean). These expectations, possibilities, limits, and constraints are direct factors in the considerations that are made when approaching a design review. How a student understand these factors will affect what questions they ask in the process and what choices they make. In other words, incorporating knowledge of genre is important to an informed and aware analysis of a writing form, even without a full genre analysis.

There are resources that are intended to help guide students, even specifically technical ones, in analyzing the context and rhetorical situation of their documents. However, it is not always clear how to apply them to the design review situation. Bitzer's "rhetorical situation" defined the context in terms of exigence, audience, and constraints. The "Rhetorical Toolbox" lists questions to ask that are familiar in the context of an English assignment. These questions are under categories of writer, audience, text and subject, and contextual spheres of production, distribution, and reception; they include references to ethos, logos, pathos; and they discuss the canons of invention, arrangement, style, and delivery and memory. It is not immediately obvious how to use these during the creation of a design review. Similarly, genre analysis proposes the ideas of etiquette or expectations that are present for types of writing. It's not a huge logical jump to agree that, as part of the "environment of the production and reception" (Shaping Written Knowledge), this etiquette and expectations can influence the typical rhetorical moves. The question, again, is how it affects a design review which does not take the same form as a standard essay assignment.

Design reviews can use text, images, CAD models, equations, spec sheets, and oral presentations. The choices of how to present, how they look, what tone, where the emphasis is or is not, and the order of information are all choices influenced by the context. The background documents that discuss design reviews touch on some of these subjects indirectly, but with less generality. They comment on the pressures of customers, bosses, governmental or regulating agencies, the need for shared purposes and cooperative attitudes, and the importance of balancing clarity, brevity, and thoroughness. This study explores the tensions, demands, influences, and other features by applying them specifically to design review creation and implementation by using more general frameworks of analysis to explore their context and contents.

METHODOLOGY OF THIS STUDY

This analysis is based on the creation and results of two design reviews and the anticipation of a final project presentation as required by the Cornell Cup competition. The first design review was the conclusion of a series of prototyping for the robot's manipulator. The second design review followed and encompassed the manipulator, prototyping for the main robot structure, and planning for the electrical and software architecture. The period after the second design review was used to construct the design, with necessary iterative testing and modifications. The competition acts as a final design presentation to evaluate how well the final design meets the initial requirements and specifications. However, the competition takes place after the deadline for this report and is therefore not included within the analysis.

The first design review was based on the knowledge, expectations, and theoretical frameworks (outlined in the Background and earlier Methodology sections) which I coalesced into a model that uses the terms stakeholders, purposes, pressures, features, and documents. My analysis of these aspects shaped how the design review was created and realized. I refined my model based on this experience, and then applied it to the second design review. Finally, based on my research, experiences, and results, I reduced the model into something that would be comprehensible in the form of a handout. The handout is intended for other engineering students to help them think about their own design reviews in a more critical manner.

Analysis of the First Design Review

The first design review occurred about seven weeks into the design process, focused primarily on the mechanical design of the manipulator, had a single presenter, and featured the project advisor as the sole member of the audience. The most complicated aspect of the context was the dual nature of the design review – it served a dual purpose as an end-of-term final presentation for a robotics engineering class at WPI. This is analogous to the many secondary purposes or expectations that can surround a design review as multiple stakeholders become invested in a design review, creating multiple purposes that must be addressed. The creation of this design review helped to frame a series of questions that formed the basis of a general approach to the process.

The model I developed as a framework for analysis during the creation of my first design review was not organized into a neat hierarchical structure. The concepts of genre, rhetoric, and context that informed my model did not present a step-by-step linear approach for analysis. Instead they highlighted the relationships between different factors that surrounded the creation of any generic document. I kept the concepts from my background material in mind as I was in the process of creating my own design review. I looked for them within the context and situation I was working in, the decisions I was making, and the documents I was producing. Many of the actions I took, the influences that informed my actions, and the products of my actions overlapped across different terms, categories, concepts, and ways of thinking that came from the multi-faceted background I was considering. I tried to identify groupings and overlapping elements and the relationships between them. As I did this I developed a flowchart to track these, which gave me new ways to consider my design review, which further developed my flowchart model My final flowchart as it stood at the end of my first design review is shown in Figure 1. The overlapping groupings I decided to assign names that I thought made sense in respect to design reviews: stakeholders, purposes, pressures, features, and documents. The process of creating the final design review documentation seemed to me to best manifest as the idea of balancing these different elements and their relations. Therefore “BALANCE” is the center block that all of the elements feed into.

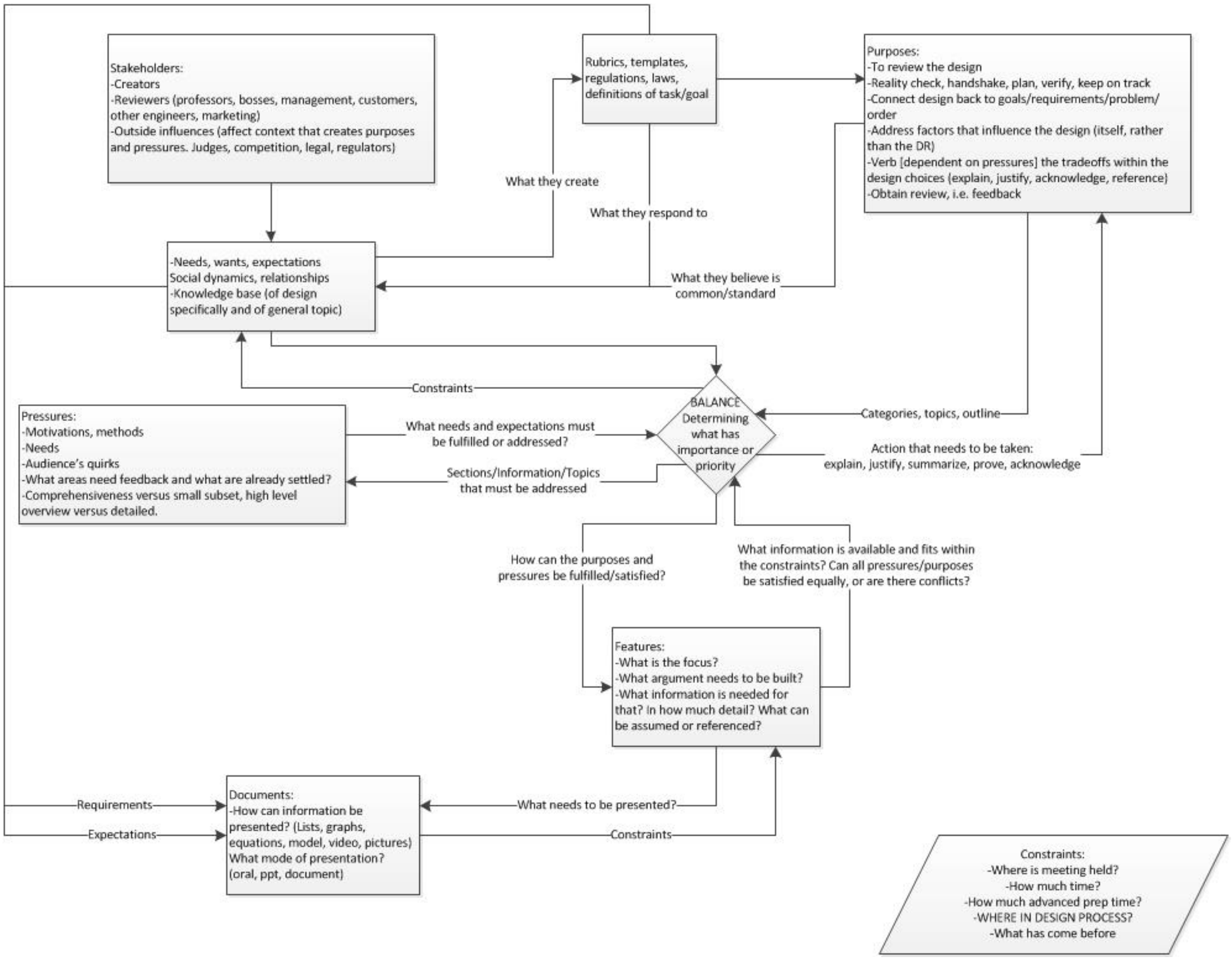


Figure 1: Defining the relationships between the components of my analytical model as based on my background research and experience. The questions go to/from the "balance" block to represent the non-hierarchical process, as the questions are asked iteratively in a process of refining their balance in the final product.

STAKEHOLDERS

The idea of stakeholders critically moves beyond the idea of an audience of listeners to a varied population who's needs and expectations for the design review help to shape its creation. Students commonly use a familiar approach of tailoring their writing to their audience. Yet the nature of design reviews makes them more of a two-way dialogue. Design reviews can also address an extraordinarily diverse set of purposes. Together, these mean that other stakeholders such as the designers and more distant authority figures can have equal impact on the design review as the audience.

The stakeholders of my first design were (1) myself, (2) my project advisor, and (3) the Cornell Cup judges. I acted as the sole designer and engineer of the project. My project advisor was both the advisor for my competition and entry and as the professor of the class RBE 540. The Cornell Cup judges were not present, but they shaped the design review by providing a required grading rubric for my advisor to fill out. The rubric encouraged the design review to support the judges' desire to have students learn professional skills such as how to develop a coherent plan by formalizing their thoughts. This context shows three species of stakeholders. The first is the designer(s) of the design review that wants to both receive feedback and justify their design choices. The second is the reviewer(s) that is concerned with giving feedback regarding the content of the design review. Finally, there is the indirect party, such as the judges or a regulatory body, which care about the motivations and methods of the design review, and perhaps the results in a general high-level sense. However, since they are not active participants in the design review meeting and presentation, they care less about the nitty-gritty of the content. These three types of stakeholders show the complexity of the environment common in the genre of design reviews.

Individuals that have gone through the modern American education system are generally familiar with the task of identifying "the audience" for their document. For example, it is not uncommon that an employee may write some report they do not believe in, merely to satisfy their boss. However, there may be parties other than the audience that influence the document, especially for design reviews. A hallmark of good writing is that it should satisfy the writer, not just the addressed audience. Design reviews meetings are essentially a dialogue: the reviewers (or writers) need to go beyond finding “satisfaction” as a general feeling to satisfying their specific needs and purposes such as the explanations, justifications, etc. and need for feedback. The designers also need the design review to serve certain purposes, such as proving their design solution meets the project’s requirements or persuading the accountants that their budget is justified or should be increased. Furthermore there may be other parties who will never see the document or attend the meeting, yet affect its creation. For my first design review, it was the Cornell Cup judges. Other instances may be regulatory or legal bodies that make certain demands or set certain standards for the design review document but do not review the document under normal circumstances. This need to address the expectations of multiple parties, that have different relationships to the document, can be understood as part of the genre of design reviews. It is inherent in the nature of them: reviewing the design in order to inform, justify, explain, question, and solicit feedback. Therefore it is crucial that new comers to the process go beyond the concept of “audience” of who is listening to the presentation to a broader idea of who needs or expects something from the design review in any significant respect.

PURPOSES

Designs are complicated endeavors with many components, choices that have various tradeoffs, and many interactions and connections between the components and choices. Design reviews are correspondingly complicated because they must find a way to handle and address all of this information. This complexity means that a design review can approach a design (as an essay can approach a topic) from any of many different possible directions. The direction of approach is defined by the set of discrete, task-based purposes the designer employs. These task-purposes are very specific. For example, “show that all of the parts fit together” or “show that the design is possible within the budget constraints.” These tasks then invoke use of features and documents as part of the design review creation. The rubric provided by the Cornell Cup explicitly lists some of these task-purposes such as resource estimate and timeline update. (Table 1) These tasks are usually the most obvious to students. However, the total quantity of any potential tasks that could be addressed within a design review is too large to fit into a single review while maintaining comprehension and fitting within any normal time constraint. This is why the curated collection of task-purposes defines the approach. Students who do not think about the specific situation of their design review may choose tasks at random, leading to a less organized, less comprehensible, and less effective design review.

The approach is chosen on the basis of broader goals. The broader goal-purposes are more general or vague than the task-purposes. For students' it may be a helpful analogy to compare the goals to essay prompts. They give a general sense of what needs to be addressed, but not specifics of how to go about that. Some examples are listed below:

- Prove the design is a valid solution
- Make and justify requests for resources
- Request and facilitate feedback
- Verify compatibility with design choices of other team members
- Verify compatibility with original need/goal/purpose of product
- Confirm thoroughness of design
- Support creation of action plan / future steps to be taken
- Act as a deadline to ensure timeliness

It is the responsibility of the designer to identify the specific task-purposes that will satisfy the broader goal. One of the Cornell Cup's goals, as specified by the rubric, asks the design review to address "General Innovation" (Table 1). The Cornell Cup website states:

> Any embedded design invention that you can dream up and create is fair game. Whether it's doing something that has never been done before, or doing something even better than ever, as long as you can demonstrate how your idea addresses an exciting challenge or important need, we want to see it. (Student Info)

Based on this information, I decided that the best way to demonstrate 'general innovation' to Cornell Cup judges would be to provide background that (1) related to the relative novelty of my combined control system and (2) connected my system design to other possible applications, such as medical use. The actions to satisfy the task would then be to discuss enough citations (explaining, comparing, evaluating, etc.) to establish (1) the novelty and (2) the similarities between my project's task and certain medical tasks. I then showed how my part related to these by showing the part through CAD and videos. The crucial question for newcomers to the design review process is *where* the goal-purposes come from, *how* do you identify the goal-purposes that need to be addressed, and *how* do you know which tasks will satisfy the goal. These questions may be harder to answer in the professional world where clear rubrics can be rare.

The "where"s and "how"s both stem from the values of the "discourse community". In genre analysis the discourse community is the population who creates and responds to a type of documents. In other words, the discourse community is the stake holders. This dialogue both occurs within a framework of shared values, goals, and accepted behaviors and redefines what is shared and accepted. These values, goals, and behaviors manifest as the purposes when applied to the specific context of a document's creation. The relation between actions and task-purposes is also defined by the discourse community in a similar way, but this will be discussed further in Features and Documents. The Cornell Cup judges, as stated on their website, value formal plans that keep different areas of the design tied to the vision of the comprehensive project. My advisor shared these goals. The broad goals in the rubric defined the focus of the design review as a comprehensive overview of the project's design because the goals covered the full time scope (what had been done so far, the current state, and the plan for the future), the different design factors (time, budget, resources, and technical challenges), understanding the context of the project (use cases and performance metrics). The designer of the design review selects their design review's approach (comprehensive overview) based on their understanding of how the stake holders' goals and values translate into broad goal-purposes. If they choose well, and execute the implementation well, the design review will satisfy the needs and expectations of all the stake holders, making it effective and successful. This is why it is important for students to think about the context and greater purposes beyond specific tasks

Table 1: The design review requirements provided by the Cornell Cup. This shows that the explanation of the system features and identifying the use cases of the problem were the most important elements to address, but that multiple factors and tradeoffs that affected the design had to be acknowledged in a balanced manner as well.

Milestone Review Rubric			
	Topic Weights	**Sub-Weights**	
Accomplishments to Date	**0.20**	*1.00*	
Functionality Status	0.13	0.65	Can you clearly identify all of the situations (use cases) that an ideal solution to this problem must handle?
Performance Measures	0.07	0.35	Can you clearly state what an ideal solution must to able to do in order to handle the identified situations?
Technical Ingenuity	**0.20**	*1.00*	
Explanation of Novel Systems / Features	0.17	0.85	What is your solution going to be able to do
General Innovation	0.03	0.15	What is your approach on how your solution is going to do it and what are the key elements to implementing that solution
Identified Complications / Opportunities to Date	**0.15**	*1.00*	
Understanding of Source	0.04	0.25	
Risk / Opportunity Assessment	0.06	*0.40*	
Mitigation / Capitalization Plans	0.05	0.35	
Project Execution Overview	**0.15**	*1.00*	Is this a technically interesting solution
Timeline Update	0.08	0.50	
Budget Justification	0.05	0.30	
Administrative Aspects	0.04	0.20	May be included as part of the Project Entry Solution Section
Recommendations & Next Steps	**0.20**	*1.00*	
Clarity of Plan	0.08	0.40	
Resource Estimate	0.08	0.40	
Performance / Functionality Gain Estimate	0.04	0.20	
Presentation Delivery	**0.10**	*1.00*	
Clarity of Slides	0.01	0.10	
Appropriate Visuals	0.01	0.10	
Organization of Presentation	0.01	0.10	
Clarity of Speaker	0.01	0.10	
Ability of Audience to Comprehend Main "Takeaways"	0.02	0.20	
Question Handling	0.04	0.40	
TOTAL WEIGHT of all Sections	**1.00**		

Pressures

For engineers, especially young ones who are still testing and practicing their design and analysis chops, it can be easy to get caught up in the technical matters as the be-all-end-all. Yet there are pressures – needs, demands, constraints, or other factors – that should affect the design review which come from the context surrounding the review itself rather than just the design. Many of these are social pressures caused by the relations and interactions between the stakeholders such as power dynamics, social relationships, varying levels or areas of knowledge, or different viewpoints and concerns. There may (or may not) be conflicts of expectations. To increase the effectiveness of the design review, these pressures should influence the balance and prioritization of the different purposes.

The pressures that mainly shaped my first design review were the differential in experience, knowledge, and authority between myself and my advisor, and the expectations that prior weekly progress reports had created. I was the sole designer and presenter of the review, so I did not have to consider any interactions with team mates, although it could be a consideration for other reviews. As a student, I had little confidence in my design choices since I lacked the long-term experiential knowledge. This also meant I held little authority in terms of my technical decisions being trusted implicitly. This led to (1) a need for me to solicit feedback and (2) a need for me to demonstrate that I had at least attempted a rigorous and plausible design process. These were complimentary to (3) my advisor's expectations that my design would be insufficient without his feedback but that I had still attempted to make a thorough design. My design's explanation was (4) constrained because I could assume or imply very little and had to provide explanations for what I was demonstrating. There was also (5) an expectation from my advisor that I would have completed an amount he considered appropriate for a seven week time frame with the (6) complimentary need on my part to fulfill his expectations. This list could be even more extensive and fine-grained, but it still shows how quickly these contextual elements can create a web of complimentary and contrasting wants that pressure the participants of the review.

A broader view of the context can expand the pressures even further. At first glance, my inexperience and lack of authority meant I had to be extremely diligent in backing my design choices. However, I had been making weekly progress reports leading up to the design review. Within these reports I had already laid out many of my design choices in detail. I had shown my sincere desire for feedback by asking for it and then acting on my advisor's suggestions. Furthermore, to go into every purpose identified by the Cornell Cup in that level of detail would strain the time constraint on my design review meeting. These exerted their own pressures, melding and altering the others. If I focused on addressing my technical design in a manner that felt implicitly "right", without critically thinking about the pressures, I could have failed to meet my advisor's expectations and created a poor grade, or I could have not received sufficient feedback to help my design and project develop. This is why it is so critical for students to critically think about what pressures exist for their design review and how they can address them.

Yet, learning to identify and act on these pressures is very challenging because by their nature they are extremely situation-specific. The individuals involved, their relations with each other, the exact sequence of events preceding the design review, and their understanding of the end goal of the project are all factors that could create some pressures, eliminate others, and offer infinite variations of most. The one pressure that is inherent in the design review genre is the tension between justifying and questioning. How the tension is resolved is a matter of the specific context, but identifying the pressures that influence the tension and its resolution should help designers balance their presentation to appropriately address the situation and fulfill the various needs, expectations, and purposes.

FEATURES

The stakeholders, pressures, and purposes lead to a series of task-purposes that must be satisfied by presenting various features or, in other words, types and sets of information. The selection of the subject matter of the features was dependent on the purposes and pressures the design review had to fulfill, and these purposes often required making an implicit argument. To determine the features, I had to determine what I needed and what my focus was, understand my audience, and choose how to structure the presentation.

There is a case to be made that the features satisfy the task-purposes and the more abstract goal-purposes, pressures, values, etc. above them by making minor, implicit arguments which are not the strongly stated claims that we typically associate with argumentation. To serve the intent of the design review, these minor arguments should be included under the umbrella of a main focus or overarching purpose, thereby collectively making a strong argument towards the bigger picture. The arguments that relate the minor claims to the main claim may be implicit arguments if there is no need, based on the on the context, stakeholders, and pressures, to spell them out explicitly. More contentious choices require stronger arguments: "I need an extra $700 of the budget to buy an expensive, custom motor" will be presented in a more explicit form by presenting a clearly stated claim ("we need this motor to meet this criteria"), supporting the claim with evidence, and providing warrants that explain how the evidence supports the claim ("we need a certain torque at a certain rpm, and this motor and gearbox combination is the only one that meets these requirements across our 5 approved suppliers"). However, other technical design choices and tradeoffs which need to be justified within the review do not need all the parts on the argument to be spelled out as explicitly. It may be enough simply to say that alternatives were considered and this one best met the requirements, full stop, without spelling out the evidence and warrants that would be necessary for an explicit, contentious argument of the more familiar form. If the reviewers trust – due to their social interactions, their expectations or assumptions, the features presented, etc. – that the presenter has done the work to support the claim, they will not question its omission and the feature of the claim alone will satisfy its corresponding task-purpose(s).

Part of optimizing the design review process is determining which arguments can be left implicit and which should be presented in a more thorough form. These decisions will be made based largely on the pressures (needs, desires, and expectations) that are influencing the design review. For example, I needed explanations to be both clear and concise but open to questioning in order maximize the quality and quantity of feedback from my advisor. I did not require detailed feedback on the design that would require mathematical analysis, structure, layout, coding, or other detailed technical discussions. Instead, I had to review my process and sequence of design choices, making an argument that the final design successfully met the demands of the problem. My advisor was familiar with the progression of my design from my weekly reports. This meant the features I could to present were the choices present for each purpose and the final selection, leaving out the decision process in the middle – in other words, presenting the claims while omitting the evidence and warrants. However, my weekly progress reports had not spent much time on the project's budget or timeline and I needed feedback on these aspects. I had to present them as my claims (that they were feasible and valid for my project), and explain how I came to that conclusion. By exposing my argument in more detail I gave my advisor more opportunities or ways to critique my reasoning which met my need for feedback.

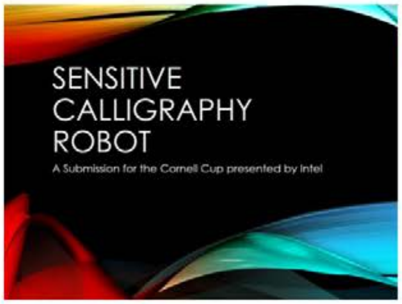
Documents

Design reviews can encompass many forms of documents: textual documents including reports or lists; numerical such as spreadsheets, graphs, equations, or budgets; drawings sketched, drafted diagrams, or modeled with CAD; documentation including photographs or video; diagrams such as flow charts, block diagrams, or layouts; or code printouts. Physical prototypes or models can also be used. Traditional design review meetings are conducted in person, there may or may not be the opportunity to share the documents prior to the meetings. These documents and their content can be presented in hardcopy form, orally, on a chalkboard/whiteboard, or in a slideshow presentation. Alternatively, design reviews may be conducted digitally, with documents uploaded in various formats. Explicit requirements and purposes and implicit pressures affect which documents should be used. There are also constraints that limit the documents.

One of the pressures I had to fulfill was the need to explain the relevant information to my advisor within the limits of the design review because he did not accept documentation prior to the presentation. Long, in-depth documents like written reports, spreadsheets, or equations take a significant amount of time to read and absorb. Therefore, it made the most sense to keep to minimal text and rely on bullet points, graphs, and pictures. Expectations and requirements can overlap. In this case both Cornell Cup (via the rubric) and my advisor expected that the design review would be conducted as a slideshow presentation. A slideshow is a convenient medium for visual images and short bullets. By presenting the information in this form of a document I could address multiple influences.

However, there were constraints on which visuals I could use. One of my task-purposes was to show that my design choices were valid by including a feature that demonstrated the prototype was operational. I could not display the full CAD model because the computer did not have the necessary software. Other visual options included screen-captures of the CAD, photos, videos, or the actual physical prototype. I had demonstrated that my prototype was operational and had passed initial testing during weekly progress reports. I referenced these demonstrations by reusing some of the same images. While in isolation these images may not have satisfactorily demonstrated that my design was valid, taking into account the other pressures and influences on the situation I was able to balance the needs with the constraints to find a satisfactory answer.

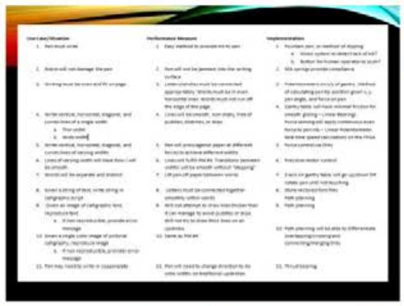
The final design review documents are shown below in Figure 2. It shows the balance between photos, drawings, graphs, flowcharts, and CAD images that are supported by references to previous weekly progress reports. The choice of these documents to convey the needed, expected, and desired task-purposes leads the audience through the design process in order to justify the decisions made so far (a goal-purpose) and provide sufficient information for the advisor to verify that the design was proceeding appropriately (another goal-purpose). In this way the design review should have fulfilled all the purposes and pressures that were part of the situational context and satisfied all the main stakeholders. For the most part, this was successfully executed. The results are discussed in more detail in the next section.

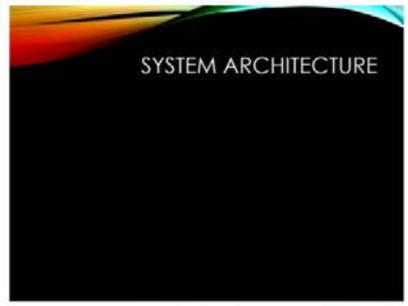

SENSITIVE CALLIGRAPHY ROBOT
A Submission for the Cornell Cup presented by Intel

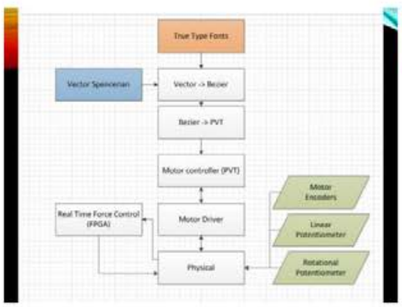

THE COMPETITION
• Embedded design competition
• Demonstrate how idea addresses an exciting challenge or important need
• Formal design process

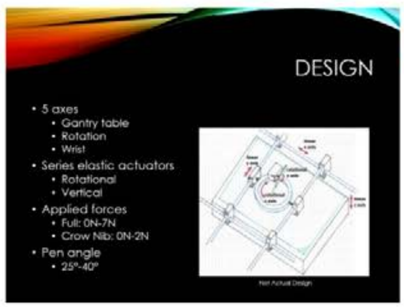

TASK
• Combine precision position control & precision force control
• Control force on pen nib to create different stroke widths
• Control position to write smooth script

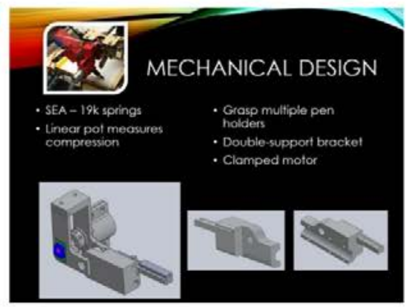

USE CASES & IMPLEMENTATIONS



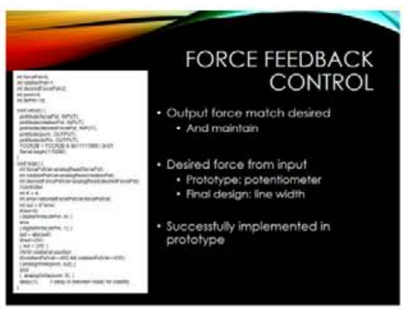

SYSTEM ARCHITECTURE

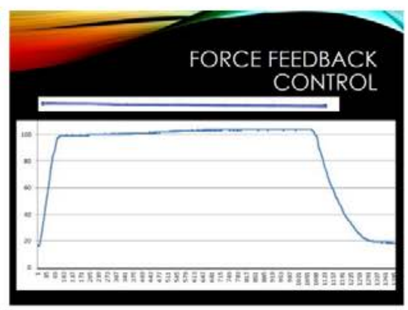

True Type Fonts
Vector Spencerian
Vector -> Bezier
Bezier -> PVT
Motor controller (PVT)
Real Time Force Control (FPGA)
Motor Driver
Physical
Motor Encoders
Linear Potentiometer
Rotational Potentiometer


DESIGN
• 5 axes
• Gantry table
• Rotation
• Wrist
• Series elastic actuators
• Rotational
• Vertical
• Applied forces
• Full: 0N-7N
• Crow Nib: 0N-2N
• Pen angle
• 25°-40°
Not Actual Design


MECHANICAL DESIGN
• SEA – 19k springs
• Linear pot measures compression
• Grasp multiple pen holders
• Double-support bracket
• Clamped motor


MECHANICAL DESIGN II
• Vertical SEA & z-axis based on GoBot
• For detecting ink dip
• Locked when writing
• Gantry system
• From Igus
• 80-20 base
• House the Intel Atom board
• Motors
• Joints: Maxon dcx 22mm
• Wrist: Maxon dcx 10mm


FORCE FEEDBACK CONTROL
• Output force match desired
• And maintain
• Desired force from input
• Prototype: potentiometer
• Final design: line width
• Successfully implemented in prototype


FORCE FEEDBACK CONTROL
100
80
60
40
20
0


BUDGET
• $1,500 from Cornell Cup
• $160 from WPI
• 2 Intel Atom Boards from Cornell Cup
• Pen nibs: free
• Motors w/ Drivers: $500
• Structure: $100-250
• Gantry System: free
• Springs: $100
• Rotation Axis: $50
• Vertical Axis: $50
• TOTAL: ~$1000


NEXT STEPS
• Order parts
• Motors, drivers, springs, 80-20, gantry
• Atom Board
• Install Windows
• Force feedback
• Finalize pen holder prototype
• Fix offsets, tolerances, etc.
• Prototype vertical SEA system


TIMELINE
• December 19th – Concept finalized
• Jan 16th – Start of C term
• Jan 24th – All parts ordered
• Jan 31st – Force feedback working via Atom Board
• February – Mid-Project Review
• March 28th – All machined parts completed
• April 4th – Fully working mechanical system
• April 24th – Project Presentation Day
• May 2nd – Competition at Disney World

Figure 2: **These are the slides for the first design review presentation. They show the focus on graphics and bullet points for easy and quick comprehension. The progression follows through the design process and ends with other external factors to build justification for decisions and facilitate desired feedback.**

RESULTS FROM FIRST DESIGN REVIEW

My presentation successfully presented my current design, facilitated feedback, and established a polite and effective dialogue between myself and my advisor. However, the review was not as successful as it could have been. The advisor graded the design review on a rubric provided by the Cornell Cup, shown below in Table 2. These were requirements made by the individuals running the Cornell Cup; providing these requirements showed that they had a stake in my design review. They explicitly provided goal-purposes, and the grade was a reflection of my advisor's understanding of their expectations and his expectations for me. There were two aspects that he considered weak: Technical Ingenuity and Resource Estimate. The reduced grade for Technical Ingenuity indicated that I had failed to properly fulfill the related purposes and pressures but the lower grade for Resource Estimate actually indicated a success.

Table 2: The grades on Cornell Cup's rubric given by my advisor on my first design review. The percentile for each category is in the "Score" column. The grades show that I successfully fulfilled most the desired purposes of the design review. However, I did not frame the challenge sufficiently for the judges (Technical Ingenuity) and some of my budget estimations were off (Resource Estimate).

Milestone Review Rubric

	Topic Weights	Sub-Weights	Score	Weighted Score
Accomplishments to Date	**0.20**			
Functionality Status	0.13	0.65	100	13
Performance Measures	0.07	0.35	100	7
Technical Ingenuity	**0.20**	*1.00*		
Explanation of Novel Systems / Features	0.17	0.85	70	11.9
General Innovation	0.03	0.15	70	2.1
Identified Complications / Opportunities to Date	**0.15**	*1.00*		
Understanding of Source	0.04	0.25	100	3.75
Risk / Opportunity Assessment	0.06	*0.40*	90	5.4
Midigation / Captialization Plans	0.05	0.35	90	4.725
Project Execution Overview	**0.15**	*1.00*		
Timeline Update	0.08	0.50	100	7.5
Budget Justification	0.05	0.30	90	4.05
Administrative Aspects	0.04	0.20	100	4
Recommendations & Next Steps	**0.20**	*1.00*		
Clarity of Plan	0.08	0.40	100	8
Resource Estimate	0.08	0.40	80	6.4
Performance / Functionaility Gain Estimate	0.04	0.20	100	4
Presentation Delivery	**0.10**	*1.00*		
Clarity of Slides	0.01	0.10	100	1
Appropriate Visuals	0.01	0.10	90	0.9
Organization of Presentation	0.01	0.10	90	0.9
Clarity of Speaker	0.01	0.10	90	0.9
Ability of Audience to Comprehend Main "Takeaways"	0.02	0.20	100	2
Question Handling	0.04	0.40	100	4
		1.00		
TOTAL WEIGHT of all Sections	**1.00**			91.525

I received a grade of 70% for Technical Ingenuity (70%). My advisor was already familiar with the problem and task my project was intended to address and knew the challenges associated with such a project. As such, I did not spend much time in my presentation, which would not be seen by the judges, setting up the context of the project. Instead, I made brief references to it and assumed that was sufficient. However, my advisor had expected me to use the design review as a kind of draft for my presentation to the judges. Since I did not fulfill this expectation, he felt the review was not entirely satisfactory. His advice focused on visuals: adding videos and diagrams that he felt would better establish the problem, its necessity, and its challenges by making them easier to comprehend, and provide a more solid foundation from which to argue that my solution was innovation in relation to the problem. However, his advice left a question: was his understanding of the expectations and needs of the judges accurate?

There is no way to definitively answer this question. It's a matter of opinion. This shows why pressures can be so tricky to effectively understand and address.

In the case of 80% grade for Resource Estimate, this actually indicated that I had successfully addressed the needs and desires of stakeholders. I had little experience in purchasing mechanical components so I presented my best estimates for the project budget but I did not have strong support for the accuracy of these estimations. I had a specific stake in the DR because I needed feedback on the budget. The lower grade shows that I was correct in identifying this as a need that had to be addressed. My advisor was able to provide better estimates and his reasoning for why he thought my numbers were off. Improved budgeting meant I wouldn't run into shortages of parts or money later on in the development process, therefore improving the overall design which is one of the largest and most overarching goal-purposes of any design review. This is a crucial part of the design review's purpose and was successfully fulfilled.

The results from the first design review confirmed that my method of analyzing the rhetorical situation and prototypical genre features of design reviews helped to create a more successful and effective design review than a less thoughtful review would have been. However, I did not catch, understand, or address properly all the dynamics and nuances as well as I could have. The model of relationships I created (Figure 1) is very complex. It has no clear start point and is not very helpful for anyone who wants clear and comprehendible help in how to create a design review. Approximately two months after this design review, I had to prepare another one. I took this opportunity to further develop and refine my understanding of the creation process so that I could make my review more successful and provide clearer assistance to other students.

ANALYSIS OF THE SECOND DESIGN REVIEW

My model (stakeholders, purposes, pressures, features, documents, and their relations) did help in the creation of my first design review by emphasizing how different factors of the context and situation could influence it. However, it had a few deficiencies. It failed to sufficiently account for the timing of the review within the design process. The constraints were also marginalized and left implicit in several of the areas. Furthermore, while the flowchart helped me, its complexity and lack of a clear starting point reduced its helpfulness for other students who would have to decipher it. The reconfigured model below (Figure 3) still brings attention to elements – such as stakeholders other than the reviewer, non-codified expectations, and social dynamics – prone to neglect or being overlooked but is easier to read than my first model.

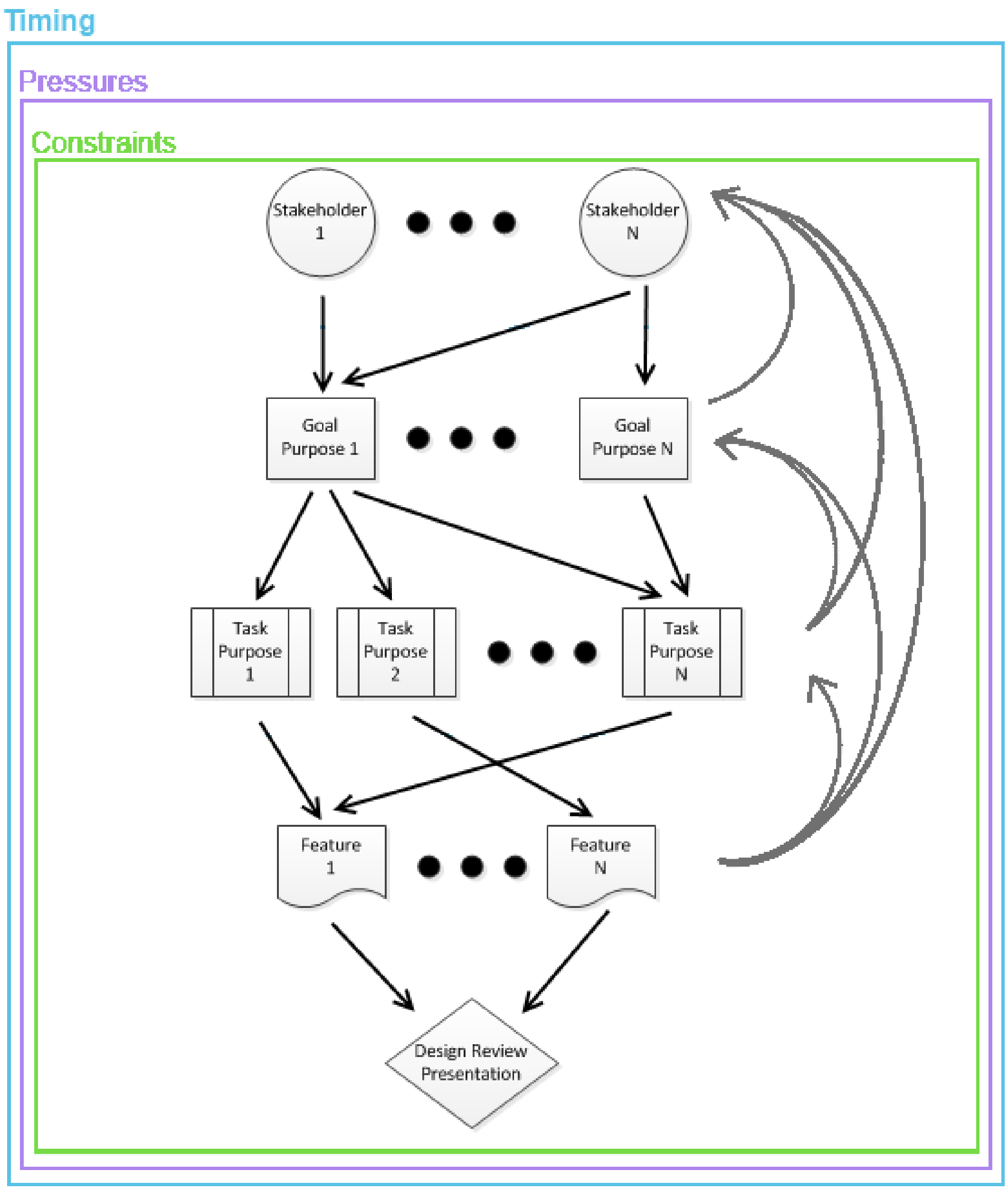


Figure 3: A more linear model of the elements that are part of a design review and their relations to each other.

The stakeholders are at the top of the progression because they tend to be easy to identify and drive the identification of many of the other implicit elements. The same as before, the designer has a stake in the DR. If part of their stake is based on a need for feedback that creates a goal-purpose, which can be satisfied by fulfilling certain task-purposes, which is done by including certain features. The same follows with the other stakeholders. The diagram labels the stakeholders 1 through N, to remind students that this is not a set variable. In my first design review I had myself presenting to my advisor with the Cornell Cup providing requirements but not present. In the second design review, myself and my two team mates each had a stake in the DR, the reviewers were two Cornell Cup representatives, and my advisor was not present but would look over the review presentation material later in order to grade it. The numbers and types of stakeholders can change. The stakeholders have needs, desires, and expectations that influence which goal- and task-purposes and features are included in the DR, how they are presented, and how much time/space is allotted to each. However, the stakeholders are still influenced by other elements.

In the initial model, the stakeholder element was one of the four main nodes that fed into the central mechanism of balancing all the inputs in order to create a design review. It was also influenced by other elements such as requirements, constraints, and beliefs/understanding. In this new model, these relations are still present through the iteration and context.

Iterative Refinement and Balancing

On the right side of the diagram (Figure 3) is a series of gray arrows that circle back to elements that are above them. This is the method of iteratively tweaking the design review. As discussed before, design reviews can persuade, justify, verify, acknowledge, confirm, question, exchange, connect, plan, reflect, uncover – whatever is needed to optimally satisfy the needs, desires, and expectations. It seems that most design reviews will have to touch on all these purposes to some extent, even if it plays a very minor role and is mostly assumed. The critical part comes in prioritizing which purposes deserve the most time and content, and balancing the different quantities devoted to the different purposes. Optimization, unless one is extremely skilled and perceptive, is usually a result of iteratively cycling through different elements, changing their prioritization and balance. This prioritization may be spelled out in part by requirements (such as the Cornell Cup rubric) but is also affected by the stakeholders since creating requirements is a clear demonstration of a stake. The other stakeholders may then be affected by the requirements. It is cyclic and iterative. Identifying a stakeholder (Cornell Cup) led to a goal-purpose (justify challenge) which led to a task (connect calligraphy to what the designers think the Cornell Cup representatives might think is a more "worthy" outcome) and then a feature (comparison between writing calligraphy and surgery) which influenced a stakeholder (the advisor) to change his desires (more focus on challenge) and *could* have added another stakeholder (a medical professional interested in the project's potential applications). Adding another stakeholder would have changed the balance of purposes and pressures. In a different example, perhaps all of the originally desired features cannot fit into the constraints of the design review – something must be cut. How does the designer decide what to cut? They must go back to one or several of the other elements, reevaluate the interactions and the intensity of the need to satisfy, and reprioritize. If, say, a goal-purpose is re-evaluated and deemed less important – based on the designer's understanding of the reviewers, the pressures, their own needs, etc. – that may subsequently make some or all of its related task-purposes less important as well, which may reduce or eliminate multiple features. This shift in balance may then provoke further revisions, and so on, until the system of elements reaches some sort of stable equilibrium in the eyes of the designer.

This balancing act is what makes pressures so crucial. Explicit purposes may be given with a rubric or a ranking, which makes it much easier. Even if they are not so clearly weighted, when the designer knows exactly what is expected, it is easier for them to weight alternatives.

However, pressures are not explicit. Their value is not stated. The designer has to recognize that they even exist before they can assign any sort of weight or importance to them. Pressures affect how stakeholders evaluate the design review and determine if it is successful. If the priority that stakeholders place on them in evaluation during the review does not match the priority the designer places on them during creation of the review, there will be a disconnect between expectations and results, and this may harm the effectiveness and success of the design review.

Context: Timing, Pressures, and Constraints

When I initially created the second model (Figure 3), I had just the elements of stakeholders, purposes, and features that proceeded one to the next, then followed by an iterative cycle back through them. I was considering including pressures by saying that they drove this process of stepping through each element. However, if they drive the process that would seem to imply that they are inherent within the creation of the design review. Yet it is easy to not consider them. I found it more useful to think of the creation process as occurring within a context and this context is defined by the pressures. If you neglect to define the context, it is entirely possible to not consider the pressures and to leave them out of the creation process. This model goes further and separates out two significant types of pressures from the rest: timing and constraints. Pressures are critical, as important as they can be nebulous, and they too encircle everything within the design review. The pressures are the distillation of the give-and-take interactions that crisscross between every element. They are wily because they are implicit, not spelled out, hidden within the interactions. Pressures shape and drive the iterative process but they also emerge from it, like an ouroboros. If they are not identified by the designer and not addressed in the design review, that is one of the most likely explanations for mismatches between the expectations, desires, and needs of the stakeholders as manifested in the goal-purposes and their reactions to the final product. Timing is in essence a specific type of pressure, separated from the general Pressures to emphasize its relative unique consistency in affecting every design review. Constraints are a pressure that must be worked around rather than alleviated or satisfied. Timing, Constraints, and generic Pressures completely permeate the design review creation and this importance is why they are represented in Figure 3 as boxes surrounding the elements, rather than enumerated as one of the elements within the progression.

Timing, or where in the design process the design review occurs, is a crucial factor. It may be considered one of the factors that most defines a design review. Throughout my research and past experience, the name or full title of the design review was often based on the timing: Preliminary Design Review for early stage DRs, Critical Design Reviews as the project is on the edge of being almost complete. The Cornell Cup specifically named one of the DRs "Mid-Project Review"; in other words, approximately halfway through the project. Timing may influence what stakeholders exist (e.g. no need for the sales/marketing team until later in the development process), the stakeholders' expectations and the DR's purposes, as well as the features that actually exist to be included (e.g. very early in the design process there might be several mockups, sketches, or rough proof-of-concepts, but it's unlikely a full-scale prototype would have been achieved yet.). Any disparity between the state of the design and expectations of "where the design should be at this stage" is a pressure that should likely be addressed in the design review. A goal-purpose may be to argue for a change to the schedule and deadlines – changing the timeline and therefore making the state and expectations match more closely. In this way, timing can directly influence stakeholders, purposes, pressures, features. It can be considering the delineating factor between subgenres of design reviews. From this view, the design review creation occurs within the context of timing and cannot escape it; hence timing is the outermost box surrounding all other elements in Figure 3. Like all elements in the design review, it is not a one-way relationship, and the idea of timing can be affected by other elements.

The Cornell Cup rubrics reflect how timing changes the design review. The Mid-Project review requirement adds greater emphasis to explaining the problem or challenge that the project is addressing and justifying how the project meets that problem or challenge. They expect by the time teams are halfway through the project, the teams have a definitive target to work towards. This expectation is not present in the earlier design review because the timing of the review means the team is less likely to have firmly established a target and the Cornell Cup representatives believe/agree with this idea of timing in relationship to the overall timeframe of the project. Here the relationships start to show the complicated web of interactions from the first model. Even though the second model is more refined in appearance, those interactions are still the basis and still present. Since timing can have such a potentially dramatic input on the final form of the design review, it is made more explicit in the second model (Figure #) by naming it separately from Pressures, which should help students remember to critically consider it in their analysis of the situation and design review creations.

In the first model, Constraints was left on its own to the side which did not reflect their interactions with the rest of the elements. This reflected how it can be difficult to see how the constraints affect choices made during the creation of the design review. Certain elements did have their own particular constraints: the need to show a prototype was working was constrained by the possible documents that could be used to that end – such as video, photos, or plots of test results – and oral or written descriptions that would be significantly more difficult to execute as desired. However, there are larger constraints that affect the entire project and it can be hard to initially articulate the exact relationships with other elements. Placing constraints as part of the surrounding context better illustrates that it can play a part of any of the decisions and choices made, and that it's a crucial part in the iterative reprioritizing and balancing of elements. Design reviews, even with the advent of technology to facilitate non-synchronous sharing and review, tend to be meeting-based. The start and end time of the meeting are likely to be defined, which both limits how much information can be contained and manifests an expectation of how much information will be contained within the design review. How much background knowledge the audience has and how much time they have to prepare prior to the design review will constrain the presentation of the information by requiring some amount of background, explanation, or justification. These constraints are examples of factors that influence the entire design review, not just one or a few elements. It is possible to make the case that constraints are just more pressures, and in some sense they are. However, they are pressures of the form "I must work around this" rather than "I must do this". Engineers are presented with limits and constraints from day 1 of their training and told to find ways to work around them and make the design successful anyways. This makes it familiar vocabulary to students and should help them identify and address these types of pressures more readily.

Results from Second Design Review

The second design review was developed concurrently with the refined model (Figure 3) and they both reflect my enhanced understanding of the creation process.

Constraints became much more significant in this review. We had to conduct our presentation over Adobe Connect screen-sharing software, which did not work well with videos, talk over a conference phone line, and adhere to a much stricter time frame than the first review. We were also constrained by the fact that the Cornell Cup representatives had very little background of our project or understanding of the specific technical aspects it included. To compensate for these we tried (Figure 4 below) to use more words on some slides in case the comprehension over the phone system was poor, and used more pictures than videos. We did leave one video in as balance, just in case the software decided to cooperate, because we could easily skip over it without a loss if it was a problem, but it would strengthen our explanation if it worked. This is an example of balancing different constraints, pressures, and purposes. Finally, to compensate for their lack of background knowledge we added more explanation in the beginning of the review about the motivation for the project, the nature of the task, and what challenges existed in the technical implementation. The features to accomplish this also related to the timing of the review.

The timing of the review created at least one explicit change in the grading rubric: they added requirements to explain the problem and how the project would address the problem. We already had to add more explanation and background to help catch the Cornell Cup representatives who were reviewers up to speed with our project. The timing was also reflected in the information we had available to present. The first design review had focused mainly on the mechanical design of the end effector. After several additional weeks, the control architecture and software design had been further developed. Also, based on the impression given by the resource documents, we believed Cornell Cup would expect us to have at least an outline of our fully integrated system by the halfway point even if it wasn't fully detailed. This was an example of how elements interact and overlap as well as how the designers' understanding of the stakeholders' expectations affects what is included in the final design.


Sensitive Calligraphy Robot
Need & Context
Position-controlled robots
– Accurate
– Poor performance in dynamic environments
Compliant robots
– Lower position accuracy
– Safer
Combined control system
– Applications esp. for surgical robots
Scope
Calligraphy as proof-of-concept
Force on nib: variable stroke widths
Position: smooth script
Use Cases & Implementations
Current Functionality
Mechanical
– Prototype for force sensing in testing applications
Software
– Development of high level motion-planning
Electrical
– In negotiation for motors and controllers
Design
5 axes
– Gantry table
– Rotation
– Wrist
Series elastic actuators
– Rotational
Applied forces
– Fountain Pen: 0N-7N
– Crow Nib: 0N-2N
Pen angle
Mechanical Design
SEA – 19lbs/in springs
Linear pot measures compression
Grasp multiple pen holders
Double-support bracket
Clamped motor
Video – Medium Line
Results
Thin
Thin
Thick
Mechanical Design
System Architecture
Software
Bezier Curves
Parametric curve
Initially used to describe auto body curves
Defined by a control polygon of N points
Most computer implementations focus on 3rd degree curves or 4 control points
What is PVT?
Method of motion profile definition
Requires Position, Velocity, and Time information
2nd order continuous motion – significantly improves stroke continuity
Bezier to PVT
Bezier are not parameterized in terms of arch length
– Very difficult to translate into PVT
Two sample methods of conversion:
– Accumulate profile mapping distance to parameter
– Search for parameter corresponding to specified distance
Conversion further constrained by mechanical limits

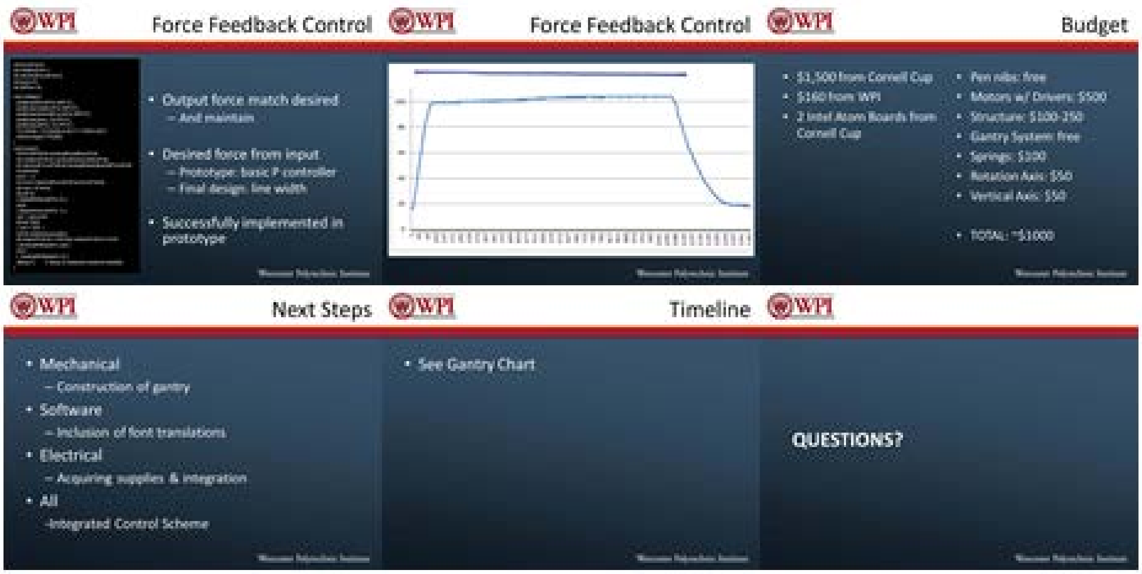


Figure 4: The slides from the second design review.

Our design review was received successfully, and was even more successful than the first. I say more successful because we received a better grade (Table 2) and more feedback for this review than I had for the first. We engaged in a back-and-forth dialogue regarding different aspects of the project's design, ways to move forward, and important considerations to keep in mind while doing so. We had successfully explained the challenges we were facing and the important aspects of our controller because the reviewers, despite initially not being familiar with the system we were implementing, were able to give us specific advice about how we could improve our controller. This shows how critically thinking and addressing some of the more complex and nuanced relations and interactions between different elements of a design review can lead to a better result.

	Topic Weights	Sub-Weights	Score	Weighted Score
Challenge Definition	**0.05**			**0.0469**
Established Need & Broader Context	0.02	0.40	0.98	0.0196
Established Scope and Main Use Cases to be Addressed	0.03	0.60	0.91	0.0273
Project Entry Solution	**0.10**	*1.00*		**0.0938**
Identification of Key Functionality	0.06	0.60	0.91	0.0546
Solution's Fit to Problem	0.04	0.40	0.98	0.0392
Accomplishments to Date	**0.10**	*1.00*		**0.0930**
Functionality Status	0.05	0.50	0.9	0.0450
Performance Measures	0.05	0.50	0.96	0.0480
Technical Ingenuity	**0.10**	*1.00*		**0.0944**
Explanation of Novel Systems / Features	0.08	0.80	0.94	0.0752
General Innovation	0.02	0.20	0.96	0.0192
Project Execution Overview	**0.15**	*1.00*		**0.1461**
Project Execution Summary	0.04	0.25	0.96	0.0360
Timeline Update	0.06	0.40	0.96	0.0576
Budget Justification	0.05	0.35	1	0.0525
Identified Complications / Opportunities	**0.15**	*1.00*		**0.1403**
Understanding of Source	0.05	0.35	0.94	0.0494
Risk / Opportunity Assessment	0.05	0.35	0.91	0.0478
Mitigation / Capitalization Plans	0.05	0.30	0.96	0.0432
Recommendations & Next Steps	**0.15**	*1.00*		**0.1397**
Clarity of Concept	0.06	0.40	0.96	0.0576
Resource Estimate	0.04	0.25	0.9	0.0338
Performance / Functionality Gain Estimate	0.05	0.35	0.92	0.0483
Presentation Delivery	**0.20**	*1.00*		**0.1914**
Clarity of Slides	0.02	0.10	1	0.0200
Appropriate Visuals	0.02	0.10	0.99	0.0198
Organization of Presentation	0.02	0.10	0.91	0.0182
Clarity of Speaker	0.02	0.10	0.91	0.0182
Ability of Audience to Comprehend Main "Takeaways"	0.04	0.20	0.96	0.0384
Question Handling	0.08	0.40	0.96	0.0768
		1.00		
	1.00			**0.95**

Table 2: Our scored rubric for the second design review. The grades for this review are consistently high, without the weak spots of the first design review.

CONCLUSION

For students learning the design review genre, I would suggest that the concept of "pressures" is the most critical aspects. The other components have more in common to the rhetorical techniques commonly found throughout our education – concepts of audience, making an argument, providing support and analysis, ensuring readability, and so on. However, pressures are the sneaky contextual elements that stem from situation-specific relationships, expectations, and interactions that are not necessarily well defined. Students that neglect to identify these risk addressing purposes, choosing features, or using documents that they may consider obvious or straight-forward but which do not effectively engage with the pressures.

Two notable forms of pressures are timing and constraints. Timing exerts a pressure on every design review because every design review occurs somewhere along the timeline of a design process. Constraints are notable because, rather than demanding that something occurs or is answered like other pressures, they demand that something *not* occur or is avoided. Specifically naming these two in addition to the more generic pressures should help students be able to better think about and identify different influences that will affect the reception of their design review and *should* affect its creation. These three – constraints, timing, and general pressures – are highlighted on my handout for other students in colors to hopefully draw the most attention to these most important elements.

It may not be necessary for a design review designer to always identify every expectation, need, or norm that circles the design review. However, I believe that I have shown it can be quite helpful to do so. Identifying and understanding them can help to tailor the design review to the specific situation, making it more effective. When I started this project, my general approach to design reviews was to cover the basics of the different technical elements, perhaps briefly mention some challenges or difficulties, and declare that sufficient. However, this process has shown me that the trite adage "you get out what you put in" holds true for design reviews too: as I have spent more time and effort in tailoring my design reviews to the specific situation I have felt more confident in my presentation and received more useful feedback. Critically considering the persons who are involved in the review and addressing them with an awareness of their expectations, your own, and how those compliment or conflict establishes a better rapport and makes the conflicts easier to address and overcome. For me, the culmination of this project is my team's final presentation to the Cornell Cup judges at the final competition in two days' time. I will spend more time and effort on discussing the value of the 8 month process that was required by the Cornell Cup (including the design reviews) rather than the merits of my final product, because I believe they value that aspect more even if I would prefer to brag about my final robot and the details of its' technical design. That preference would have been indulged if I did not have this project's analysis to help me reflect thoughtfully on the situation.

For students, critically analyzing the context of their design review could seem unnecessary or extra work in the low-stakes environment of student design reviews. However, design reviews are a common tool that is used across a huge swath of different industries. In some cases, missing unspoken assumptions can be dangerous, as may have contributed to the Three Mile Island disaster (Guillory 121). If students practice identifying and incorporating these ways of thinking about these different elements and approaching the creation of their design reviews it may become second nature. In other words, they will "[develop] new ways of thinking to take from being a student into becoming a high achieving professional" (Cornell Cup) and be "[enabled] to handle any other [technical presentation] he may later be required to use" (Childs 395). I hope that my handout will help to guide their critical thinking process and make it seem like less work than having to analyze the process from scratch as I have done. The handout is included on the next page, at the very end of this report.

How to Create a Design Review

Design reviews are a common and important tool across technical disciplines. A successful review can significantly improve your design and make the project run more smoothly. A successful review is dependent on more than just covering the basics of your technical design. Here are important elements and questions that should help guide the creation of your design reviews to make them more effective.

1. Timing: When is your design review occurring within the design process? The timing changes what is important, what information is available, and the expectations that stakeholders have.

2. Stakeholders: Who cares about the design review? Think about more than just the audience: yourself, higher authorities, third parties...

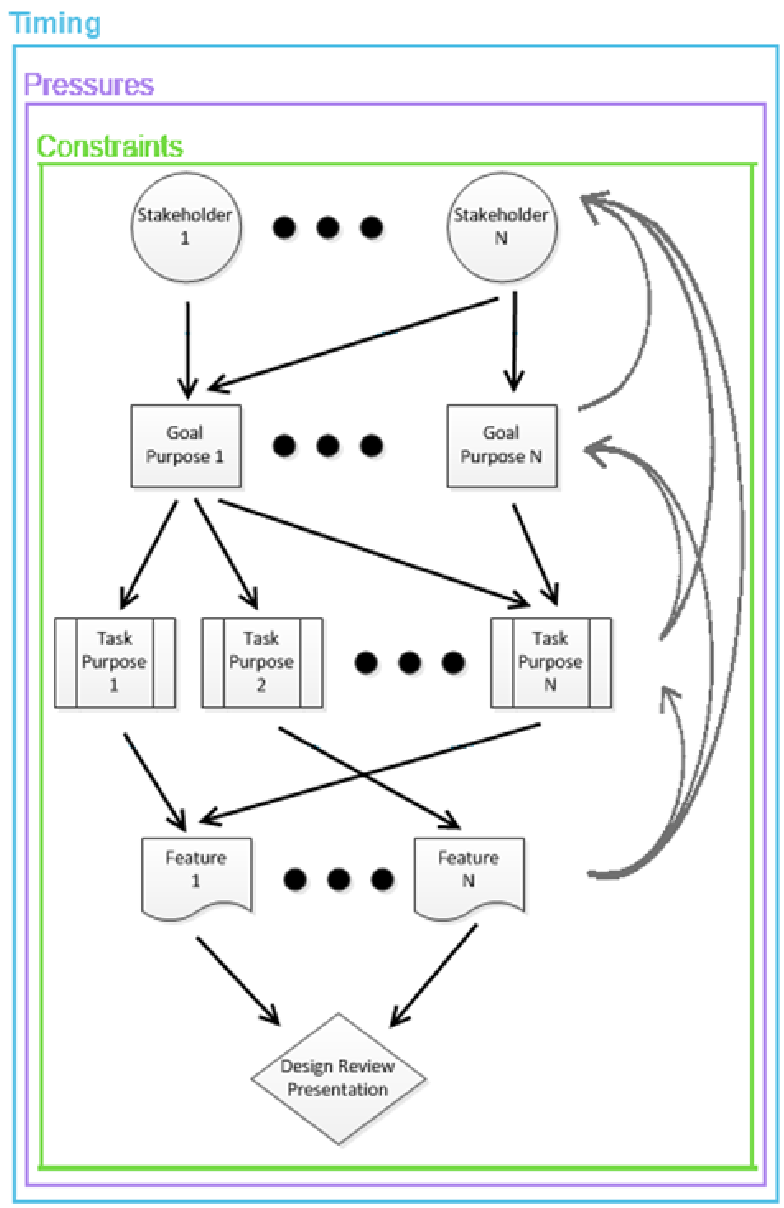
3. Pressures: These are not explicit, or stated straight out. They tend to arise from the social dynamics between stakeholders and between stakeholders and the other elements. A common pressure is the need to balance between justifying and explaining your design choices and soliciting feedback.

4. Constraints: What will limit your review? Is there a time limit? A specified format? How much background does the audience have?

5. Goal-Purposes: These are broader and more abstract: what is the point of the review? Example might be, show this challenge is worth solving and that your design will address it or prove the prototype is a viable solution.

6. Task-Purposes: These are the specific ways you address the goal-purposes. You might demonstrate a prototype is viable by showing the physics have been accounted for, and/or showing an assembly can be constructed, and/or that the prototype meets certain tests.

7. Features: The information used to fulfill the tasks and how you present the information. You could show equations or a stress analysis; a video of a test, a graph of measurements, or the actual prototype.



8. **Iteration**: These elements are all interdependent on each other. You might choose features based on certain pressures, but that choice might create a constraint that will limit the number of tasks you can address. It's important to go back through the different elements and questions until you find a balance.

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