April 8, 2013

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Dear Professors,

The enclosed final design report has been prepared in accordance with the course requirements of MTE 482. The report summarizes the process undertaken to design and construct an *Automated Laparoscopic Suturing Tool*. The project has been completed and successfully meets all of the constraints set out at the beginning of the project. In accordance with an agreement with the Toronto Hospital for Sick Children, the tool will be delivered within the month for further research. The design team will not be involved in further research or development related to the delivered tool.

The described project successfully designed and constructed a robotic suturing tool which will be used for academic research into the viability of performing fully automated surgeries. The project focussed on the electromechanical design of the tool, while SickKids will develop the vision guided control algorithm. Once the tool has been combined with the vision guidance, the tool will be capable of truly automated suturing.

The enclosed report has been written solely by the listed authors and has not received any previous academic credit at the University of Waterloo, or any other institution. Any use of content or figures from previous design reports has been cited appropriately. The group would like to thank Professor Huissoon for his help throughout the project, as well as Andrew Urschel and Phil Laycock for their invaluable assistance during the prototyping phases of the project.

Sincerely,

Brock Kopp	Karl Price	Angelica Ruszkowski
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DEPARTMENT OF MECHANICAL AND MECHATRONICS ENGINEERING
UNIVERSITY OF WATERLOO

Automated Laparoscopic Suturing Tool

MTE 482: Final Design Report

April 8, 2013

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Group 11

Executive Summary

The Automated Laparoscopic Suturing Tool project is being completed in conjunction with the Centre for Image Guided Innovation and Therapeutic Intervention (CIGITI) at the Hospital for Sick Children in Toronto, Ontario. The project has been undertaken in accordance with the capstone project requirements for the University of Waterloo MTE481 and MTE482 courses. The project is defined to create the electromechanical components of CIGITI's *KidsArm* system. The requirement is for an automated tool capable of performing automated laparoscopic suturing for minimally invasive surgeries. The scope of this project involves the mechanical and electrical designs, low-level control design and prototype manufacturing of the tool. CIGITI will be responsible for ultimately completing the high level suturing control. Since the tool is being designed as part of a research project with CIGITI, there are no intentions of commercializing the suturing tool.

The commercially available Covidien SILS Stitch tool is used as a platform since it offers gripping and needle-toggling capabilities in one mechanism. The project design is elegantly interlaced with the mechanisms of the SILS Stitch, achieved through three iterations of the design process. The design cycles also allowed for the optimization of the design criteria, the most critical of which are weight and needle passing success. The weight must be minimized since the tool will be mounted on a 6-DOF robotic manipulator in CIGITI's lab, and any additional weight adds complexity to the dynamics and control of the manipulator. Needle passing must be successful because a dropped needle incurs large time delays and introduces difficulty to the operation. The entire purpose of automating the suturing task is to expedite the suturing process and reduce operation times.

The final mechanical design is an elegant, stacked form manufactured from lightweight nylon material. An additional degree of freedom was added to the final design, thus the completed tool includes continuous end-effector roll, pitch articulation, continuous body roll, gripper opening/closing, and needle toggling/loading actuation modes. Position feedback on each of these ensures accurate precise control is available. The electrical design is efficient and reliable, and is presented in a modular fashion. The PCB is encased in the electronics box with commonly used interfaces available. A serial connection (USB) to the Arduino UNO microcontroller allows for easy control of the tool. A simple application programming interface is offered, along with a user-friendly graphical user interface which permits control of each of the actuation modes.

The project was completed on schedule and under budget. There were some avoidable shipping costs which might have been prevented with more forethought when purchasing development materials. For the majority of the project timeline, however, development went smoothly. Minor challenges were faced with the final prototype concerning the additional degree of freedom. It is recommended that a new, significant feature not be added in the final iteration of a design process so that there is time to overcome any unforeseen complications prior to the final design manufacturing.

The automated laparoscopic suturing tool developed for this project will be handed off to the CIGITI lab at the Toronto Hospital for Sick Children in a few weeks. First, a transfer package must be composited for the CIGITI lab group. This package will not only contain two functional prototypes and the electronics box, emergency stop and required cables, but also intricate design details (e.g. drawings), an instruction manual, all software interfaces and necessary documentation. A presentation will be prepared to explain any critical information and to formally hand off the project. A PhD student is currently developing vision control algorithms to control the robotic manipulator and perform fully automated suturing. It is expected that bench testing of the automated suturing will begin during the summer of 2013, and animal testing may commence as early as 2014.

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1 INTRODUCTION

1.1 BACKGROUND

The medical field is constantly evolving in pursuit of increased efficiency (cost and patient wait times) with optimized accuracy. While these objectives are often contradictory when relying on human surgeons, the field of robotic surgery is an evolving field with promising potential. A robotic system, if accurately controlled, can greatly increase operating room efficiency by automating common, repetitive tasks. The focus of this project is laparoscopic surgery, which is a type of minimally invasive surgery within a patient's abdomen.

FIGURE 1 - COMPUTER RENDER OF FINAL DESIGN MOUNTED ON A DENSO VP6242

Minimally invasive surgery provides significant patient benefits by reducing patient trauma and recovery time. However, these advantages come at the cost of increased difficulty for surgeons. Since the surgeon must access the surgical site exclusively through small incisions in the patient, the long tools required to reach the surgical site lead to magnified hand tremors and reversed hand controls. As a result, seemingly simple tasks such as suturing (sewing tissue) can be tedious and time consuming operations.

The Center for Image Guided Innovation and Therapeutic Intervention (CIGITI) at the Toronto Hospital for Sick Children aims to implement robotic solutions to improve many aspects of surgery. One of CIGITI's projects is to build the *KidsArm*, a fully automated surgical suite. By automating routine surgeries, the *KidsArm* will save operating room costs and wait times by leveraging the enhanced reliability and precision of a robotic system. One of the many tools used by the *KidsArm* system will be a suturing tool. This tool will be used by the system to stitch patient tissue along an identified path.

This suturing tool will be mounted on a 6-axis industrial robotic arm, the Denso VP6242. The suturing tool described in this report will work in conjunction with its parent robotic arm to perform suturing tasks.

1.2 NEEDS ASSESSMENT

Due to the complications of minimally invasive surgeries described above – namely magnification of hand tremors, reversed controls, and limited visibility in the surgical site – performing repetitive tasks in a minimally invasive operation can be challenging even for the most highly trained surgeons. Herein lies a perfect opportunity for automation and robotics to greatly benefit the process of repetitive, high-precision tasks. An optimized process results in shorter operation time and less trauma for the patient. The safe and efficient performance of surgical operations is the main motivation behind CIGITI's new project, the *KidsArm*. The *KidsArm* is destined to be a fully automated, vision-guided robotic surgical suite. It is to be the first technology of its kind in the world.

The first benchmark operation of the *KidsArm* is performing a suture (or sewing up a wound). Suturing is often a very time-consuming task during an operation, so making this task more efficient can result in significant time savings in the operating room. Thus the Toronto Hospital for Sick Children has expressed a need for a robotic surgical tool to be mounted on a Denso arm to comprise the electromechanical component of the *KidsArm* project. The tool must be able to perform automated laparoscopic suturing by accepting control signals and returning key feedback signals. Once completed, CIGITI will accept the tool and continue development of the vision-guidance algorithms and dynamic models to control the 6 degree of freedom (DOF) robot manipulator.

1.3 Problem Formulation

1.3.1 Problem Statement

Develop an automated, laparoscopic suturing tool for use in minimally invasive surgeries.

1.3.2 Constraints

As identified in the MTE481 final report, the tool was designed and constructed to satisfy the following constraints:

i. The weight of the tool shall not exceed 2.5 [kg]
ii. The cost of the final tool shall not exceed $1000
iii. The tool must fit through the trocar, thus the shaft diameter must be less than 10[mm]
iv. The tool must achieve high repeatability: joint resolution to $\pm 5^{o}$.
v. The tool must successfully bind the suture pad (99.5 % success rate)
vi. The tool end-effector within the remote center of motion (RCM) must have 6 degrees of freedom
vii. The tool must provide accurate position feedback

1.3.3 Criteria

As identified in the MTE481 final report, the following criteria were developed in order to compare different proposed designs and identify design strengths and weaknesses:

i.	Weight	[kg]
ii.	Cost	[$]
iii.	Tool size (especially shaft diameter)	[mm]
iv.	Accuracy of actuation/articulation of end-effector	[rad]
v.	Ease of automation	[hrs]
vi.	Ease of manufacturing	[hrs]
vii.	Simple controller API	[hrs]
viii.	Maximize robot workspace with tool mounted	[rad]
ix.	Minimize damage to surrounding tissue	[qualitative: amount of residual material, harm to immediate area, etc]
x.	Optimize reliability (repeatability, accuracy)	[%], [rad]
xi.	Maximize aesthetic appeal	[qualitative]
xii.	Minimize power consumption	[W]

1.4 DESIGN REVIEW

The final build of the robot was based on two previous design iterations. Detail on these iterations is provided in Section 2. The goals of this final design were:

1. Minimized weight
2. Focus on aesthetics
3. Standardize all aspects of design
4. Add body roll degree of freedom

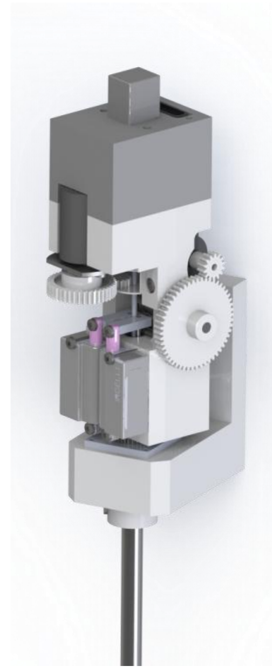


FIGURE 2 - FINAL DESIGN SUCCEEDED IN MEETING ALL CRITICAL DESIGN CRITERIA

With the complete design fully assembled, the design team has reflected upon the many additional improvements made. They are presented in the following paragraphs.

The first notable improvement is that this iteration is mainly **manufactured from plastic.** Cast nylon was chosen for its high strength-to-weight ratio. All structural pieces were machined from this nylon. This represented roughly a one-third weight reduction due to main structural members in the final product when compared to prototype 2 which was machined from aluminum. The final weight of the prototype was 639 grams. This weight satisfied the weight requirement of 2.5 kg. The white plastic also lends itself to a **clean aesthetic appearance**, which can be compared to that of a new plastic surgical tool.

The **compact design** of prototype 2 was used as the basis of this final design iteration. It lends itself well to good aesthetic presentation and lightweight design.

In order to further reduce weight, new **lightweight gears** were used to replace the steel gears from prototype 2. Tough nylon gears were suitable for use with the wrist roll and pitch actuation modules, and aluminum gears were used for the body roll, which experiences high torque.

All joint accuracy criteria were met with the exception of the wrist roll joint. The wrist roll joint has a backlash of 16.8^{o} which exceeds the initial criteria of 5^{o} resolution. The effects of this backlash as discussed in Section 3.5 where the performance of the tool is analyzed in depth.

The **body roll** degree of freedom was added in this revision. This allows the tool shaft to continuously rotate above the pitch joint. This required the addition of one stepper motor and an extra set of gears.

An **aesthetic cover** (shown in dark gray in Figure 2) was added to conceal the electrical wires connected to sensor and actuators on the tool. It also provides housing for the DVI connection on the tool. This part was printed with a 3-D printer out of nylon.

The **tool shaft was shortened and strengthened.** The shaft was shortened to allow the robot holding the tool to have a larger workspace within the operating cavity when it is holding the tool. The shaft was made out of 3/8" (9.53mm) stainless steel tubing for this iteration. This allowed the shaft to take the additional torque applied to it by the mechanism of the body roll, as well as fitting through the 10mm trocar. The stainless steel shaft also opens the possibility of additional sterilization methods being used on the tool, since the stainless shaft is quite robust.

A **printed circuit board** was designed for this iteration of the tool. The printed circuit board allows for reliable electrical connections and a clean electrical presentation. All **electrical connections** to and from the driver box were **standardized** to use commonly available cables. This allows for a better end-user experience.

Finally, the last three design constraints were achieved. The tool has proven to bind the suture pad with more than 99% success. The tool also has six degrees of freedom within the surgical cavity. The final cost of the tool came in under $1000. $2800 was spent on the production of three prototypes, including development costs.

2 PROTOTYPES

It was determined early in the project that multiple tool prototypes would be required in order to produce a final product adequate for academic research with the Toronto Hospital for Sick Children. A schedule was developed to produce three separate prototypes of evolving designs throughout the course of the year-long project. Each subsequent prototype would build upon lessons learned from weaknesses in previous prototypes.

2.1 INITIAL DESIGN

The initial prototype was developed as a proof of concept for the multiple mechanisms designed to actuate the base tool. Since the module would use a Covidien SILS Stitch end-effector as the platform, it was necessary to assure that it was in fact possible to effectively interface with the SILS Stitch. This design focused principally on proving the viability of separate mechanisms, rather than size or weight criteria. This was done under the assumption that the design would be refined in future revisions. Design simplicity was paramount at this stage of the project.

All motors were actuated using an electrical design prototyped on a simple breadboard. This simple circuit layout was a temporary design, simply meant to ascertain that the selected motor drivers and Arduino microcontroller were capable of performing their required tasks.

This prototype was completed according to schedule in early December 2012. Three of four degrees of freedom were fully functional, while the needle toggling function struggled to successfully pass a needle between gripper arms. With functional separate mechanisms, design on a second prototype was begun.

2.2 SECOND DESIGN

The second prototype was developed with the goal of producing a fully functional prototype which could be delivered to the client. While it was never intended to deliver this prototype to CIGITI, this design would allow the group to identify any shortcomings in the final design and rectify them prior to the completion of the project.

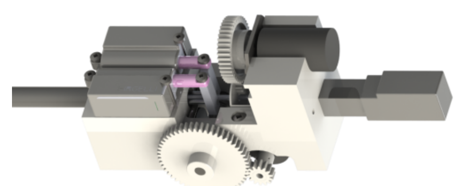


FIGURE 3 - SECOND PROTOTYPE, FULLY FUNCTIONAL BUT ALUMINUM BODY IS HEAVY

The second prototype offered great size reduction from the first prototype. Significant effort was expended to create a compact module that could easily be mounted and controlled on a robotic arm. The most significant difference between the first and second prototypes is the multi-layered design adopted in the second prototype. By placing the pitch module on the underside of the tool body and the needle toggling actuators on top, the tool's footprint is reduced by more than 50%.

The electrical circuit designed for prototype 2 was fully implemented on a permanent perforated breadboard. These soldered connections were much more reliable than the original prototyping board. A layout was carefully designed to minimize the size of the single layer circuit, with solid core wires used to provide connectivity between pins. While this design was effective, it was very bulky and the many exposed wires did not have the appearance of a complete and reliable circuit. As such it was determined that a final design would have to be implemented on a printed circuit board.

While the first prototype was primarily functional, there were issues successfully toggling the position of the needle. These issues arose from an effort to interface with the SILS Stitch's manual toggling mechanism. These efforts failed and as a result the manual toggling mechanism was opened up to expose the internal control rods. Prototype 2 utilized two linear actuators which interfaced directly with the end-effector's control rods. This allowed much greater control over the end-effector position and proved to be very effective.

The second revision was so effective that the design team approved it to be fit for use for CIGITI. While minor modifications were possible, all desired functionality was implemented. With over a month left before the project's completion, the decision was made to extend the final design's functionality to include an extra degree of freedom, the body roll. The addition of the body roll would greatly increase the tool's workspace within the surgical site.

3 Final Design

3.1 Final Design Details

The final design consisted of five independent degrees of freedom (DOFs). These DOFs allow the tool to both position itself within the surgical site as well as perform suturing operations. With three positional DOFs, the tool is able to perform suturing without relying on any movement from its parent robotic arm. This will greatly simplify the coordination of multiple tools operating at one time since all robotic arms will be working very close to one another in the *KidsArm* surgical system.

Pitch

The end-effector's pitch DOF allows the gripper arms to rotate radially from the shaft of the tool. Similar to a human curling its wrist, this degree of freedom is critical for reaching positions within the surgical site not aligned with the entry incision.

FIGURE 4 - PITCH DOF

Body Roll

The tool's outer roll DOF allows the entire tool to rotate axially about the tool shaft, irrespective of the robotic arm's current position. This roll allows the tool to change the plane in which the end-effector is pitching. This DOF can be compared to a human rolling its forearm.

FIGURE 5 - BODY ROLL DOF

Effector Roll

The tool's end-effector roll allows the tool to rotate the gripper jaws below the tool's pitch joint. This roll is used to orient the tool's jaws parallel to the tissue it is attempting to suture.

FIGURE 6 - EFFECTOR ROLL DOF

Gripper

The tool's gripper DOF allows it to open and close its gripper jaws shown in the figures on the right. By closing its jaws, it is able to pierce the patient's tissue with the needle. It is only when the gripper jaws are closed that the tool can pass the needle through the patient's tissue.

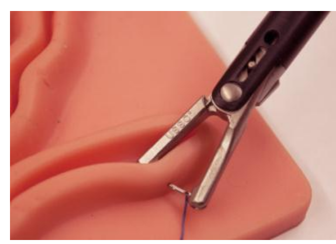


FIGURE 7 - GRIPPER DOF

Needle Toggle

Toggling the tool's needle refers to the action of passing the tool's needle through the patient's tissue. To do so, the tool must first close its jaws about the tissue. Once closed, the needle is disengaged from one jaw and engaged with the jaw on the other side. Once the jaw opens again, the needle has been successfully passed through the patient's tissue.

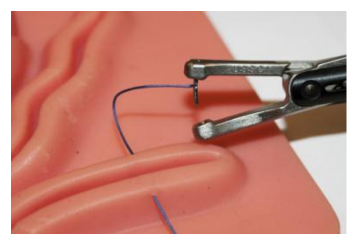


FIGURE 8 - NEEDLE TOGGLE DOF

3.1.1 MECHANICAL

The mechanical design of the final prototype was very similar to the second prototype, not including the addition of the outer roll. Since the tool will be mounted on a robotic manipulator, size and weight of the prototype can have significant influences on the system dynamics and thus the complexity of the manipulator controls. The following sections describe the mechanical design of the more complicated assemblies.

PITCH SPOOL ASSEMBLY

One of the most intricate mechanical assemblies on the tool is the pitch spool assembly. The end-effector is actuated by two control cables which are kept under tension at all times in order to minimize play. As such, a mechanism had to be devised which could reliably keep both cables tensioned, while precisely actuating the end-effector pitch. Figure 10 shows the final design, with a single shaft with two spools controlling the position of each cable. These cables are counter-wound about their respective spools, allowing the mechanism to release one cable while it tensions the other at the same time. By placing both spools on a single shaft, the cables will always be tensioned proportionally even in the event of a failure.

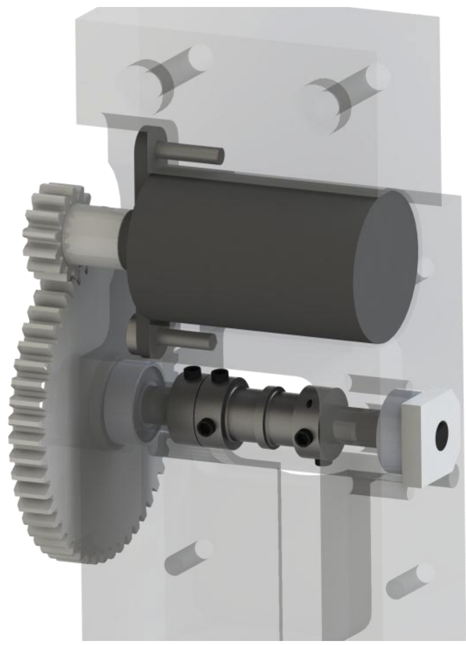


FIGURE 9 - PITCH SPOOL ASSEMBLY: NEATLY INTEGRATED INTO TOOL CHASSIS

The single stepper motor (black) drives a pinion which in turn drives the shaft gear. This mechanism has a mechanical advantage of 3.71, allowing a relatively small motor to drive the cables under significant tension. The gearing also presents the additional advantage of increased resolution by the same factor. Finally, a non-collocated encoder is located independently of the motor to assure that the controller can determine the exact location of the pitch, even in the event of the motor skipping steps under high load.

WRIST ROLL ASSEMBLY

The tool's wrist roll assembly is critical for orienting the gripper in a position to grab the tissue to be sutured. The base tool's existing compound gear box was used since it was purposefully built for the task. This allowed the stepper motor's large gear to easily interface with the roll shaft which ultimately moved the end-effector. The roll gear was selected to have a gear ratio which was the inverse of the gearbox's. By negating the gearing of the gearbox, one revolution of the drive motor would result in exactly one revolution of the end-effector. As such, the rotational encoder could be located on the motor shaft rather than attached to the drive shaft, which would have been much more difficult. While the gearbox ultimately provided no mechanical advantage, it was necessary in order to interface with the roll shaft.

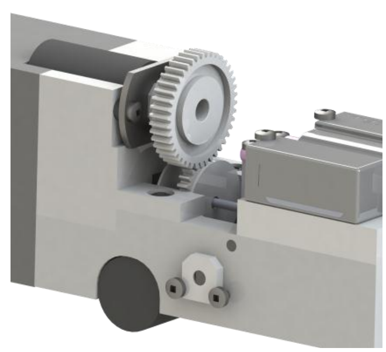


FIGURE 10 - WRIST ROLL ASSEMBLY: INTERFACE DIRECTLY WITH SILS STITCH GEARBOX

Outer Roll Assembly

The outer roll assembly is responsible for rotating the entire tool about its shaft. Figure 11 shows the small drive motor and the planetary gear train which rotates the tool. A sun gear is fixed to the mounting plate with a 1:1 gear ratio with the planet gear. The 1:1 gear ratio sacrifices required torque, but allows the encoder located on the motor drive shaft to read the exact position of the tool, where as a smaller planet gear would have necessitated a more complicated encoder placement.

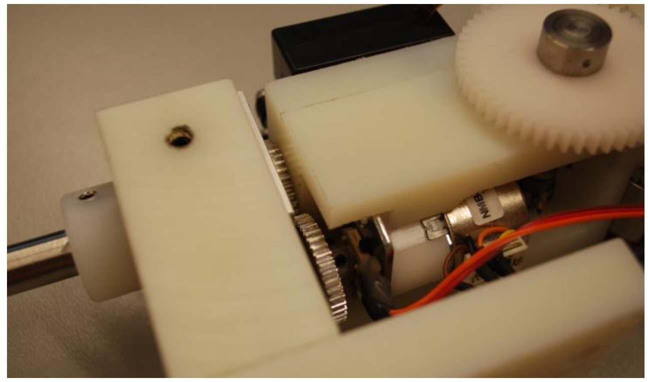


FIGURE 11 - OUTER ROLL ASSEMBLY: SUN GEAR CONFIGURATION FEATURES ALUMINUM GEARS FOR HIGH TORQUE TOLERNACE

The drive train for the outer roll assembly is very compact since the drive motor is located in the underside of the tool, requiring almost no extra space. While the drivetrain is compact, the mounting bracket could not be made as compactly since the thin shaft and long tool required that the ball bearings be placed at least 1” apart in order to reduce tool wobble.

3.1.2 Electrical

Electrical Overview

The electrical layout consists of five main parts:

- **Power:** A 12V, 4A power supply runs directly to the motor drivers. The microcontroller board is powered by its USB connection to a computer. This serves as a safety feature to ensure that the robot will not move if the controller is not connected to a computer. An emergency stop switch is connected to disable the power to the motors when enabled.
- **Microcontroller:** A “Boarduino” (Arduino implementation) is used to control the robot. A serial connection runs to a USB port of a computer and powers the micro controller as described above.
- **Motor Drivers:** Three stepper driver chips are used to drive the stepper motors (details in Appendix V). They can output a maximum of 2A to the motor, and feature an active current limiting circuit. This allows the stepper motors to be overdriven to output the torque that this application requires of them. Three H-bridge chips are used to drive the linear actuators. They are rated to comfortably handle driving the linear actuators at their maximum rated current draw.
- **Actuators:** Two sets of actuators are used. Three stepper motors and three linear encoders. A more in-depth look at the actuators will be presented in the following section.
- **Encoders:** Every actuator has a position encoder attached to it. The linear actuators have linear potentiometers incorporated in them and the stepper motors have continuous rotary encoders mounted on the affected rotating shafts. A more in-depth look at the encoders will be presented in the following section.

Figure 12 shows the high-level electrical layout of the driver board. A printed circuit board was designed and created that allows for easy assembly of these components. A labelled photograph of the board is included in Appendix V.

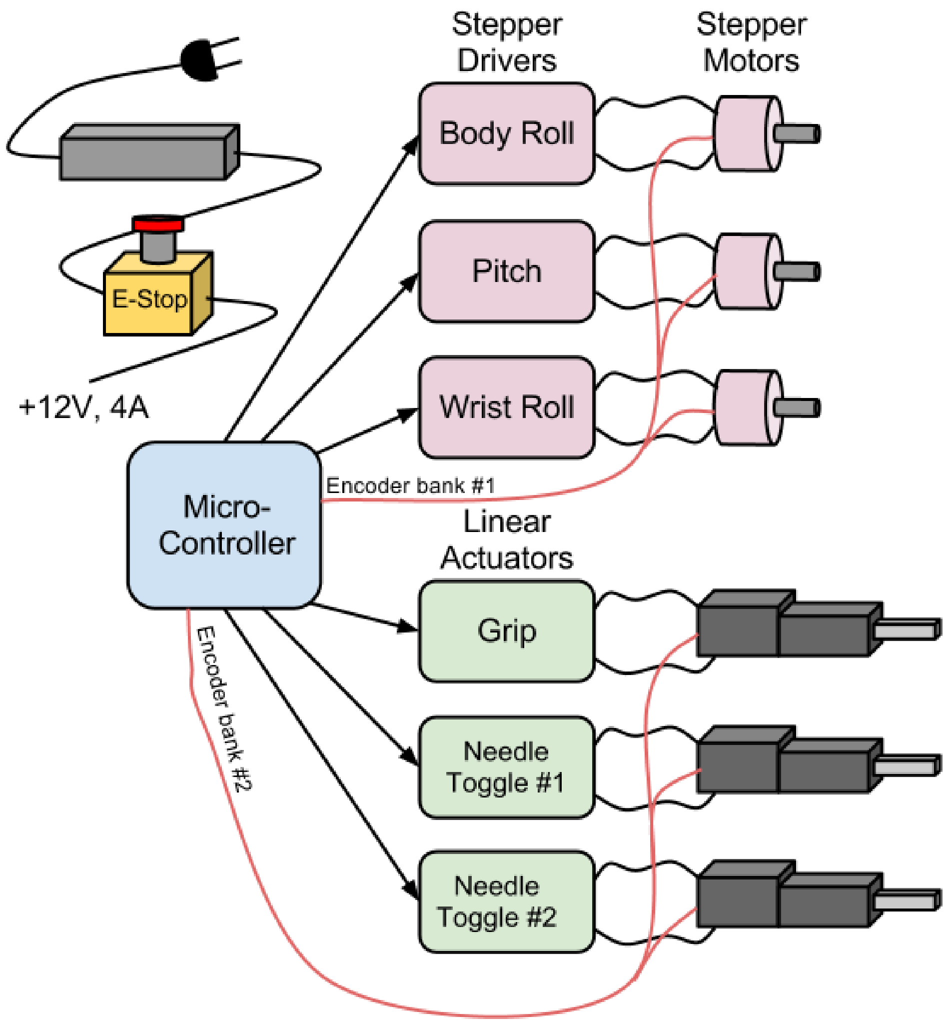


FIGURE 12 - ELECTRICAL OVERVIEW

Sensors and Actuators

Steps were taken during the design phase to standardize parts whenever possible. This led to the incorporation of one model of stepper motor, and two models of linear actuators. One model of a discrete position sensor was used. The main sensors and actuators used in the design are presented in this section.

Stepper Motors

A 22mm diameter geared stepper motor was used to drive all three positional degrees of freedom (body roll, pitch and wrist roll). This motor was chosen for its small form and light weight, which were unmatched for the torque output it can generate. The motor is shown in Figure 14.

FIGURE 13 - GEARED STEPPER MOTOR WITH LIGHT WEIGHT PLASTIC GEARBOX (SOURCE: DIGIKEY)

These stepper motors have a step angle of 0.1^{o} – 0.5^{o}, and with a rated current draw of 350mA, they can be comfortably overdriven with the chosen stepper driver chip, which can output a maximum of 2A to the motor.

Linear Actuators

Linear actuators were used to drive both needle toggle arms as well as open and close the gripping end-effector. The Firgelli PQ12 and L12 series of actuators were chosen for use in this design. They are small and lightweight as well as very accurate. The actuators have a built in potentiometer which is used for position feedback. This sensor allows for positional accuracy of 0.25mm. A diagram of the L12 actuator, which is used to control the grip degree of freedom, is presented in Figure 15.

FIGURE 14 - FIRGELLI L12 LINEAR ACTUATOR WHICH FEATURES 0.25MM RESOLUTION (SOURCE: ROBOTSHOP).

Rotary Encoders

Rotary encoders are incorporated with each of the stepper motors to provide positional feedback for the positional degrees of freedom (gripper open/close and needle toggling). The encoder used is the Bourns Rotary Position Sensor. It functions as a continuous potentiometer. It features analogue resolution which is discretized to 1028 bits by the microcontroller. A small deadzone is inherent in the encoder which allows for inaccuracy between the +/- 5^{o} range.

FIGURE 15 - CONTINUOUS ROTARY ENCODER WITH ANALOGUE RESOLUTION USED ON ALL ROATRY JOINTS (SOURCE: DIGIKEY).

ELECTRICAL STANDARDIZATION

Great care was taken to make the drive electronics of the robot compatible with standard cables. This was considered important so that the client would not be inconvenienced by a short or lost cord, as they could easily purchase a replacement cord from any electronics store. The electrical connections are summarized below and shown in Figure 17:

- **Power:** standard laptop-style power cord barrel connector
- **Serial Communication:** USB cable
- **Motor Power & Logic Transmission to Robot:** DVI cable

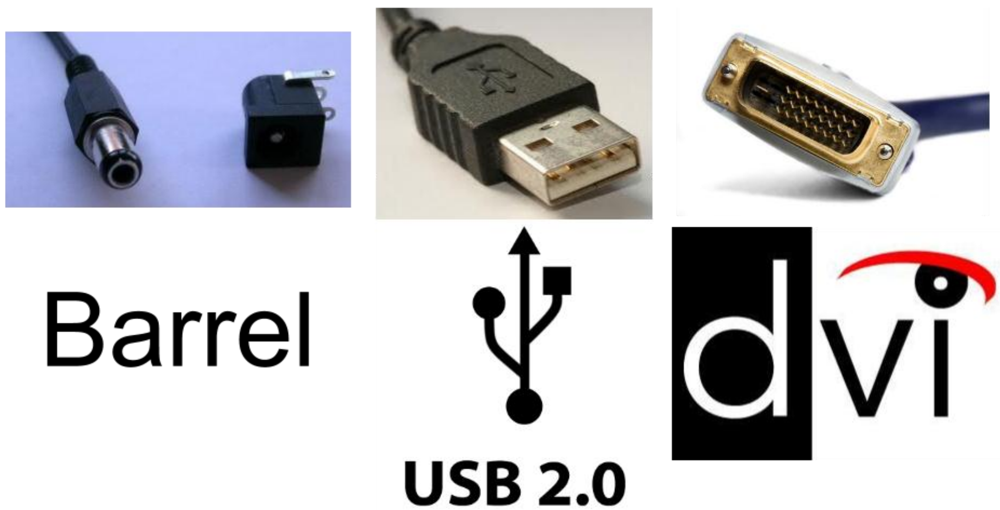


FIGURE 16 - STANDARD CONNECTORS USED IN FINAL ITERATION ALLOW FOR A BETTER END-USER EXPERIENCE

3.1.3 SOFTWARE

The goal of the software design is to have a modular, light-weight software and controls package with an easy-to-use interface. The main tasks required of the software are to

- Control actuation points (six actuators)
- Handle feedback appropriately
- Offer simple interface

i. *Controlling actuation points*

The software must be able to control each of the six actuators with precision. Due to the properties of the Arduino UNO microcontroller, serial commands are used. The limits of serial connections, however, are that only one output/input may be processed at a time – i.e. one cannot simultaneously control multiple actuators with high precision. There are complex methods of accomplishing this through software, however speed is not critical and performing sequential joint actuation is sufficient to satisfy the project constraints.

The actuators being used are either stepper motors or linear actuators. In an effort towards modularity while keeping efficiency and hardware limitations in mind, one C++ class was written for each of these. Both include a `int getPosition()` function and a `void goToPosition(int desiredPosition)` function, however the stepper motors move in units of degrees while the linear actuators move in units of millimeters. Various verifications are performed to ensure an actuator does not exceed its functional range to prevent any mechanical damage.

ii. *Handling feedback appropriately*
Each linear actuator is driven by an H-Bridge which includes potentiometer feedback from the actuator, and each stepper motor is paired with a continuous-rotation rotary potentiometer. This results in six feedback signals. Since a serial connection is being used, only one actuator will be enabled at a time, thus only one signal must be monitored at a time. This allows for high precision in controlling the actuator motion. The feedback is constantly verified to ensure the actuators do not exceed their rated range of motion.

iii. *Offer simple interface*
A multi-character menu was developed to offer an easy-to-use interface to control each of the actuators. The acceptable user commands are tabulated in Appendix V. Each input parameter must be delimited by commas and the command must be terminated by a newline character. For example, a command to move the body roll by 10^{o} clockwise would be “`OR, +D, 10 \n`”. A general command is composed of <module>, <direction><unit>, <value>.

3.2 Modifications From Original Design

Major modifications were made between the initial and final prototypes as the group became better acquainted with the intricate challenges of the problem. While the initial prototype did successfully actuate each of the degrees of freedom required, it did so in a rather crude manner. One of the actuation modes (the needle toggling) definitely needed improvement since interfacing directly with the SILS Stitch toggle arm did not provide sufficient control and accuracy of the toggle action – the most critical of all the actuation modes. Further, the initial prototype was heavy, large in volume, and mechanically not the most elegant design. The electronics were in a prototype stage, with lots of redundant connections yet creative solutions to support all the extra wires. Multiplexers were used in the first design to accommodate the connections with the limited Boarduino I/O pins.

The final design, described in detail in the previous section, had been optimized through three full design cycles to reach its final state. Mechanically, each of the actuation modules were moved to a more compact design. Stacking the modules allowed for a smaller volume and accordingly smaller chassis. The weight of the design was further decreased by switching to nylon for the construction material. Weight was a key constraint for the project. While all designs were well under the 2.5kg requirement, minimizing the weight would benefit further development in the *KidsArm* project since the tool would be mounted on a 6-DOF robotic manipulator. Determining an accurate dynamic model for the manipulator becomes increasingly more challenging when there is a heavier tool mounted on the manipulator’s end-effector.

Another mechanical modification was the additional of an extra degree of freedom – the body roll. Due to the fact that the pitch joint only articulates in one direction, adding a continuous roll above the pitch joint dramatically increases the workspace of the tool’s end-effector. Attaching a module to house the body roll motor and mount the tool resulted in additional weight, however upon feedback from CIGITI the cost of the additional weight is less than the benefit of the additional degree of freedom.

A final mechanical addition was the inclusion of a cap to encase the electrical wires leaving the tool. Mechanically the tool looks sleek and compact. The electronics were also optimized to match the elegance of the mechanical design. At the tool, the wires were routed to a DVI connection such that a DVI cable can be plugged into the electronics enclosure cap. The group sought to use common components that would be convenient to replace in case of damage or desire for a longer cable, for example. The DVI cable connects on the other end to the control board. The control board had been completely redesigned to a more efficient, reliable layout. Several redundant lines are tied together, obsoleting the requirement for the multiplexers. A PCB was designed by the group and fabricated by a sponsor, Bittele Inc. The PCB is encased in the electronics box, a plastic box with a DVI connector to the tool, a USB connection to communicate serially to the Boarduino microcontroller, a push button to reset the Boarduino, a power switch, and LEDs to indicate power. Finally, an e-stop is included in the circuit for additional safety. The box, PCB, and e-stop come together as a complete electronics package which offer aesthetic appeal and will simplify use for the end user.

3.3 Manufacturing

The final design was manufactured primarily out of nylon plastic. Nylon was selected due to its high strength-to-weight ratio, allowing the final design to be compact and light, yet still stiff enough to last years of operation. All base parts were machined using a milling machine in order to achieve the precision required by a surgical application.[1] While a strong plastic, nylon is still significantly weaker than metals such as aluminum alloys and as such care had to be taken when working with small features such as threads or mounting slots.

TABLE 1 - PLASTIC MATERIAL COMPARISON

Material	Tensile Strength [psi]	Density [kg/m^3]	Strength / Density
ABS	4100	1039.97	3.942
Acrylic	10000	1189.97	8.404
PVC	7500	1419.96	5.282
High Density Polyethylene	4000	959.97	4.167
Nylon	**12000**	**1149.97**	**10.435**
Polypropylene	5400	909.97	5.934

Nylon gears were used for all power transmission requirements except fo the body roll. The body roll module used aluminum gears due to the higher torque experienced by this degree of freedom. Nylon was chosen for the other gears since it offer weight savings, and although not as strong as equivalent steel gears, nylon again offered much better comprimise between strength and weight.

Rapid prototyping acrylic was used to build the wire cap located at the top of the tool (dark grey in Figure 2). Rapid prorotyping was used since the cap is hollow and would result in much less material waste than any material-removal process such as milling.

3.4 Commissioning

The automated laparoscopic suturing tool described in this project was developed for the specific needs of the CIGITI research group at the Toronto Hospital for Sick Children. The final product is the electromechanical component of CIGITI's *KidsArm* project, which will continue development over the summer and subsequent year towards the goal of a completely automated surgical suite with suturing as the first benchmark operation. Since the *KidsArm* is the only system in the world of its kind, there are few (if any) other clients or potential markets

[1] http://www.curbellplastics.com/technical-resources/plastics-properties-table.asp?cols=1&compare=&direction=asc

which could benefit from the use of this product. Opportunities may arise if other research labs commence similar automated surgery research projects, or if CIGITI requires tools for other tasks such as knot tying or suturing through a 5mm trocar (the tool described in this report was designed for a 10mm trocar). The automated laparoscopic suturing tool is a component of a very niche project, and is not really practical or feasible as a commercial product at this point in time. However by the end of April the final product will be handed off to the PhD student at CIGITI who is waiting for this tool to continue development of his vision guided algorithms.

In terms of patentability, while this is the first fully automated laparoscopic suturing tool which combines gripping and needle passing in one tool, there may not be possibility of patenting any work done for this project. The automated tool developed for this project is based on the SILS Stich tool by Covidien which holds the patents for the mechanisms of the gripping and needle toggling. There is potential for patenting the process through which each of the degrees of freedom modes are actuated, however this will require further research.

3.5 Testing and Performance

Once the third revision of the tool was build and fully assembled, the testing phase began. The core functionality of the tool was understood based on the previous design iterations of the tool, however, the final tool needed to be characterized and proven. Three types of testing were performed:

- **Repetition Testing:** Each joint was actuated to its extremities one hundred times. This typically took about a half hour per joint. Once the repetition testing was complete, the group was confident in the joint's ability to actuate reliably.

- **Resolution Testing:** Each joint was moved in its smallest increments to determine what the smallest achievable resolution of the joint would be.

- **Repeatability Testing:** Each joint was moved to a specific point within its range, moved back to zero, and then back to the target point. Measuring against a fixed marker, the repeatability of the joint was determined.

Joint Performance

The following joint performance was obtained using the resolution and repeatability tests described in the previous section.

TABLE 2 - JOINT PERFORMANCE CHARACTERISTICS

	Range	Resolution	Backlash
Body Roll	Continuous	0.12^o	2.3^o
Pitch	70^o	0.05^o	1.75^o
Wrist Roll	Continuous	0.12^o	16.8^o
Grip	45^o	N/A	N/A

Roll

The backlash observed on the wrist and the body rolls is present due to machining error. The body roll backlash is small enough to be considered acceptable. The wrist roll backlash is undesirable. Through use tests however, it has been observed that the backlash present serves often as a benefit. As the grip closes to pierce tissue, if the wrist does not have the optimal orientation, the tolerance provided by the backlash can allow the wrist to re-align itself properly. This was observed to happen repeatedly, and can act to remedy the seemingly high backlash characteristic of the wrist joint.

Pitch

The pitch has shown successful performance. The range achieved was on par with projections based on initial prototypes. The torque exerted by this joint has proven to be able to hold the joint rigid during normal operation.

Grip

The grip joint has also shown successful performance. The gripping power exerted by the grip exceeds that necessary to suture on the standard phantom suture pad. Throughout the entire development process, a needle jam had not occurred due to the gripper not being closed.

End-Effector and Needle Toggling

The needle was toggled 100 times on a repetition test with no needle jams and no needle drops. Ensuring that the needle is not dropped during a surgery is extremely important. The results obtained through repetition testing of the needle shows that dropping the needle will not be a concern.

A standard phantom suture pad was used to test the thickness of tissue through which the tool could pass a needle. It has successfully passed the needle through the thickest portion of the suture pad which represented the most difficult tissue the tool would be expected to suture.

Speed

With the exception of the needle toggling, the speed of every joint far exceeded the required speed of operation of the tool. The speed of the joints was therefore reduced to increase the resolution of the tool and to present the tool as a more reliable, slow, and calculated instrument.

4 Schedule and Budget

4.1 Schedule

A project timeline was decided upon in September 2012 with the goal of creating two prototypes and one final construction. The plan was to have the first prototype built by early December 2012, the second prototype built for late January, and the final prototype built for early March, with a safety margin before the symposium mid-March. The team was a little bit behind schedule for the majority of the project, experiencing minor delays in various facets of the project. However, due to the safety margin which was allotted, as well as frequent short-term planning meetings held to keep the project on task and nearly on schedule, the team was able to complete all three prototypes, two of which met all constraints and were fully functional, within the allotted time. Thus the team is able to hand off two copies of the tool to CIGITI. A detailed Gantt chart is available in Appendix III.

4.2 Budget

The group is very thankful for the generous support it has received from its contributors. Robert Wagner (a technician for the Mechanical and Mechatronics Engineering Department) assisted in manufacturing a component for the final prototype. Bittele Inc. fabricated the final PCB free of charge. Educational Training Systems donated its Denso arm for the symposium. The Mechanical and Mechatronics Engineering Department is offering $75/person/term (a total of $450), and the Toronto Hospital for Sick Children offered financial support as well.

In summary, the project came in under budget. The cost expectations changed as the group's expectations for prototype development evolved. The initial expectations for the budget (for a single prototype), drafted in September 2012 are as follows. The actual expenditures exceeded these initial estimates, however the group did not exceed its available funding.

TABLE 3 - INITIAL BUDGET EXPECTATIONS

Actuation			
Motors	5	$ 100.00	$ 500.00
Gears	6	$ 40.00	$ 240.00
Miscellaneous Mechanical Components	1	$ 50.00	$ 50.00
Electronics			
Ardunio Board	1	$ 70.00	$ 70.00
Miscellaneous Components	1	$ 100.00	$ 100.00
Motor Drivers	5	$ 30.00	$ 150.00
Sensors			
Flex Gauge	1	$ 30.00	$ 30.00
Rotational Encoder	1	$ 60.00	$ 60.00
Optical Sensors	1	$ 10.00	$ 10.00
Linear Encoder	1	$ 65.00	$ 65.00
Rotational Encoder	1	$ 60.00	$ 60.00
Material			
Plastics	1	$ 150.00	$ 150.00
Subtotal			$ 1,485.00
Taxes			$ 193.05
TOTAL			**$ 1,678.05**

After the development of three prototypes (two of which are fully functional), as well as purchasing extra components for back-up for either the symposium or for the end-user at CIGITI, the final budget is summarized below. The values for each of the categories already include taxes and shipping costs. A detailed budget is included in Appendix IV.

TABLE 4 - FINAL BUDGET

Item	Value
Electronics (sensors, actuators, PCB components)	$ 1,685.48
Mechanical (gears, material, fasteners)	$ 663.98
Miscellaneous (e.g., carrying case)	$ 336.30
TOTAL	**$ 2,685.76**

It can be seen that the budget did expand during the design cycles, but the initial budget did not consider the purchasing replacement/back-up components, neither did it include certain expenditures such as the carrying case ($250). Granted, these purchases were made for the benefit of the end-user and were not made without support from CIGITI.

5 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the project was concluded both on time and under budget. The final product impressed the director of the CIGITI research group (the end-user) at the symposium, and the presentation was award-winning. The team managed to complete three prototypes, two of which were fully functional and satisfied all criteria and constraints. The two acceptable prototypes will be handed off the CIGITI mid-April to be used as the electromechanical component of the suturing operation which serves as the benchmark task for the *KidsArm* completely automated surgical suite.

Significant improvements were done between the first and final prototypes. The mechanical design was optimized to make the tool's footprint more compact by stacking the actuation modules. This decreased the volume of the tool, as well as the weight. The weight was further decreased by using nylon as the manufacturing material. It is critical to decrease the weight as much as possible to reduce the complexity of dynamic models for the robotic manipulator upon which this tool will be mounted. An additional degree of freedom was also added in the final prototype – the body roll. This additional degree of freedom is above the pitch joint, which dramatically increases the workspace of the tool's end-effector.

Electronic improvements were also made and resulted in a more reliable and efficient final design. The number of connections between the control board and the robotic tool were reduced, allowing for the reduction of components in the circuit. A PCB was also designed and fabricated, adding a level of professionalism to the electronics. The PCB is encased in the electronics box which offers common interfaces to transmit control signals to the robotic tool and to communicate between a computer and the microcontroller.

The software written on the Boarduino microcontroller offers modular joint control and an easy-to-use serial command structure which can be integrated with programmatically or through the GUI application which has been provided. Redundant software checks ensure that no mechanical damage can be suffered.

The team functioned very successfully, each member taking on major responsibilities but assisting each other throughout the whole process. Frequent meetings ensured the project remained on schedule and meticulousness in spending and recording expenses ensured that the project came in under budget.

For future projects, it is recommended to think more proactively when ordering components. Nearly 10% of the group's spending was spent on shipping costs. Often the group found itself in a situation where it needed replacements for one or two components from suppliers from which the group had very recently placed an order. For example, four separate purchases of stepper drivers had been made throughout the course of the project. Collaborating with other teams who use the same suppliers could also reduce shipping costs.

Another recommendation would be to not include a largely novel feature in the final design cycle. The group should have evaluated its desire to include the body roll between prototypes 1 and 2, not 2 and 3. Several challenges were experienced with the development of the body roll, and ultimately some design flaws were made. While the modifications necessary to repair the flaws are clearly understood by the group, including this feature in prototype 2 would have allowed for discovery of these flaws earlier on and their elimination from the final design.

Since this project has been developed for a specific end-user, it is suggested that the group now compiles a transfer package which will be presented to CIGITI. This package will include the two functional mechanical tools, the electronics box, e-stop and required cables, a clean software interface (both code-based and a GUI application), as well as documentation on how to use and interface with the tool. A presentation should also be prepared to explain any important information and formally hand off the project.

6 TEAMWORK EFFORT

6.1 BROCK KOPP

Brock Kopp was the 'Mechanical Lead' for the project. In this role he was responsible for partially designing the first prototype and subsequently designing all mechanical aspects of the second and third prototypes. Brock was able to make large improvements to the original mechanical design, resulting in a much more compact and effective final tool. Brock also performed the majority of the manufacturing work as he was most familiar with the designs and had an extensive machining background.

Brock also worked with Angelica with software implementation once the fabrication of the final prototype had been completed. Brock focused on developing the multi-input serial command interface with which the robotic tool would be controlled. This interface would allow the robot to be controlled via a simple set of ASCII commands, which would be both human readable and simple for an automated algorithm to utilize.

Throughout the project Brock oversaw purchasing for the group. Brock assured that submitted orders were neither redundant, nor missing key components. This was very important since there were three group members needing parts at all times and shipping costs had a significant impact on the group's final budget. In an effort to further mitigate costs, Brock contacted a local printed circuit board supplier (Bittele PCB Assembly, Toronto) and was able to obtain approximately $200 goods-in-kind sponsorship for the project.

6.2 KARL PRICE

Karl Price was the Project Manager for the duration of the project, and also took on the role of 'Electrical Lead'. He aided in organizing the group and delegating tasks to individuals. Initially, Karl procured funding from the Toronto Hospital for Sick Children for the project. He has worked with the CIGITI research lab at the hospital for three work terms and there obtained robotics development experience that he applied to guide the direction of the project. He continues to be the main point of contact between CIGITI and the design group.

Karl aided with the initial mechanical design as well as the manufacturing of all three prototypes. He also designed and built both electrical layouts. During the month of January, he built the prototype electrical layout, and then designed and assembled a PCB for the drive electronics of the robot. By involving himself in these elements of the project, he was able to develop useful forethought while planning the next directions for the project. This allowed the group to complete project goals on time.

In the final stages of the project, Karl has been focusing on planning and readying the final product for presentation to CIGITI.

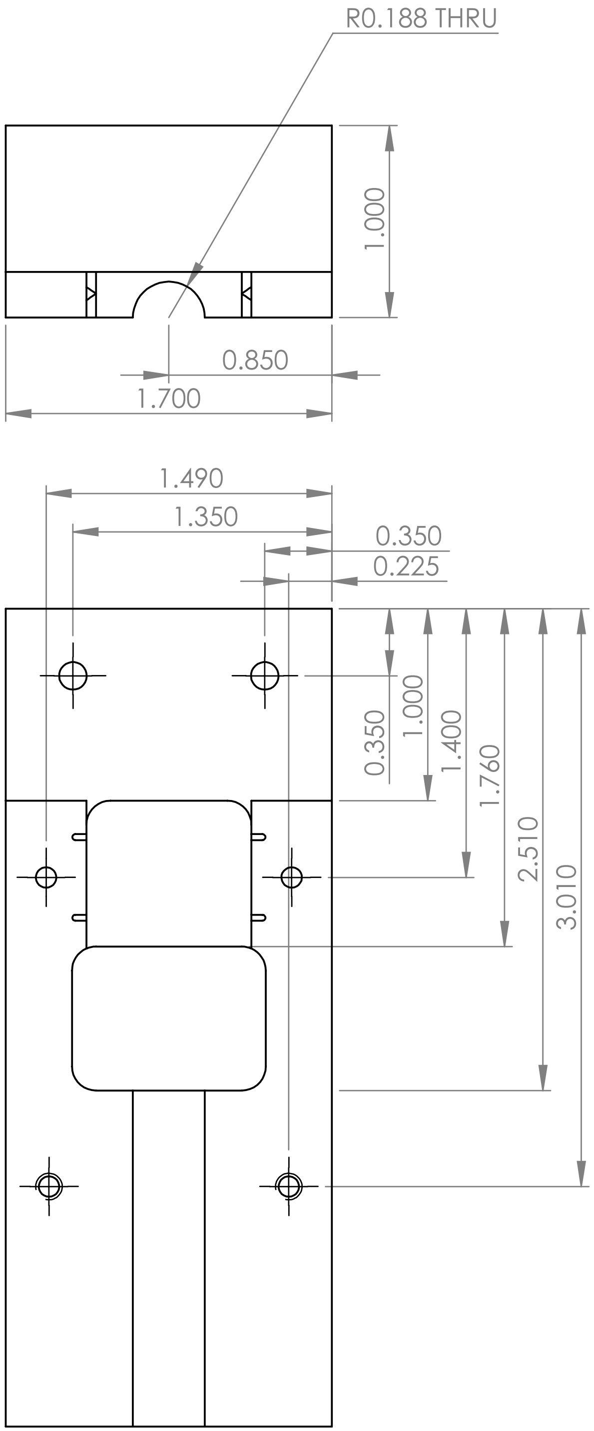
6.3 ANGELICA RUSZKOWSKI

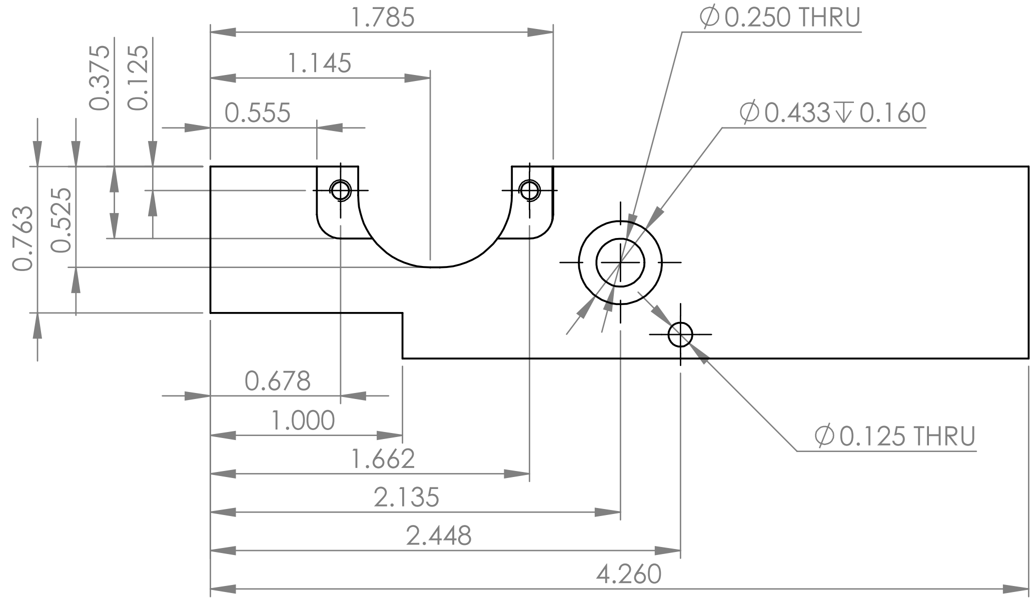
Angelica Ruszkowski was the 'Software Lead' for the project. Her responsibilities included developing the base libraries and logic for communicating with and controlling the automated tool. Using modular C++ classes, Angelica developed code to interface with the sensors and actuators through the multiplexers in prototype 2, and then ultimately with just the microcontroller. Firmware and software needed to be carefully designed due to hardware limitations (namely restricted RAM). Angelica developed a single-input serial ASCII command structure which was improved by Brock to a multi-character, more user-friendly interface. She then took Brock's multi-character algorithm and incorporated it into an easy-to-use GUI application.

Willing to be involved in the other facets of the project, Angelica assisted in the initial electrical development, and contributed heavily to the manufacturing of the mechanical components of the final prototype. She was also responsible for monitoring the budget throughout the course of the project.

Angelica was also the publicist for the project. She designed and developed the website, and then produced the poster with significant input from her colleagues. Creating a strong presentation at the symposium was critical for the group, so Angelica sought out Educational Training Systems and borrowed their Denso VP6242 – the exact model that will be used at the Toronto Hospital for Sick Children – to provide context for the symposium presentation.

7 APPENDIX I : DRAWINGS





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	MFG APPR.		
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MATERIAL Nylon 6-10	COMMENTS:		
FINISH Mill			
DO NOT SCALE DRAWING			

AutoSut

TITLE:

Enc. Bottom

SIZE	DWG. NO.	REV
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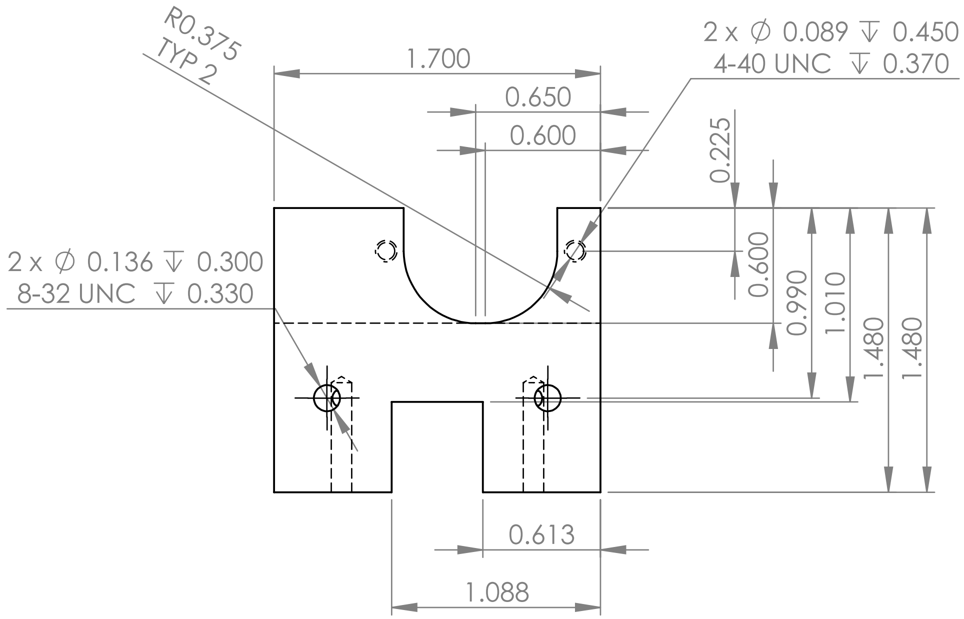

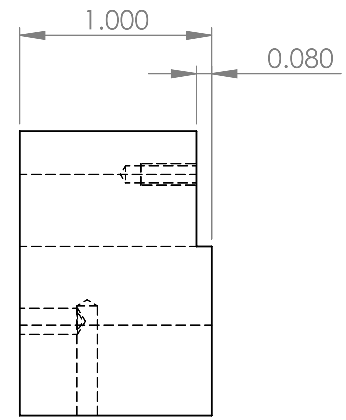

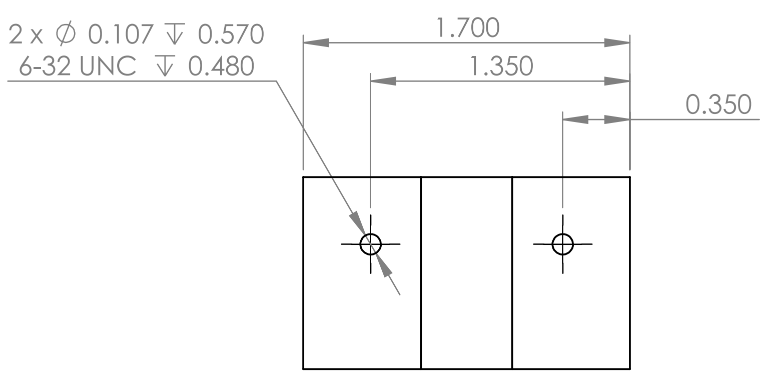

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	MFG APPR.			
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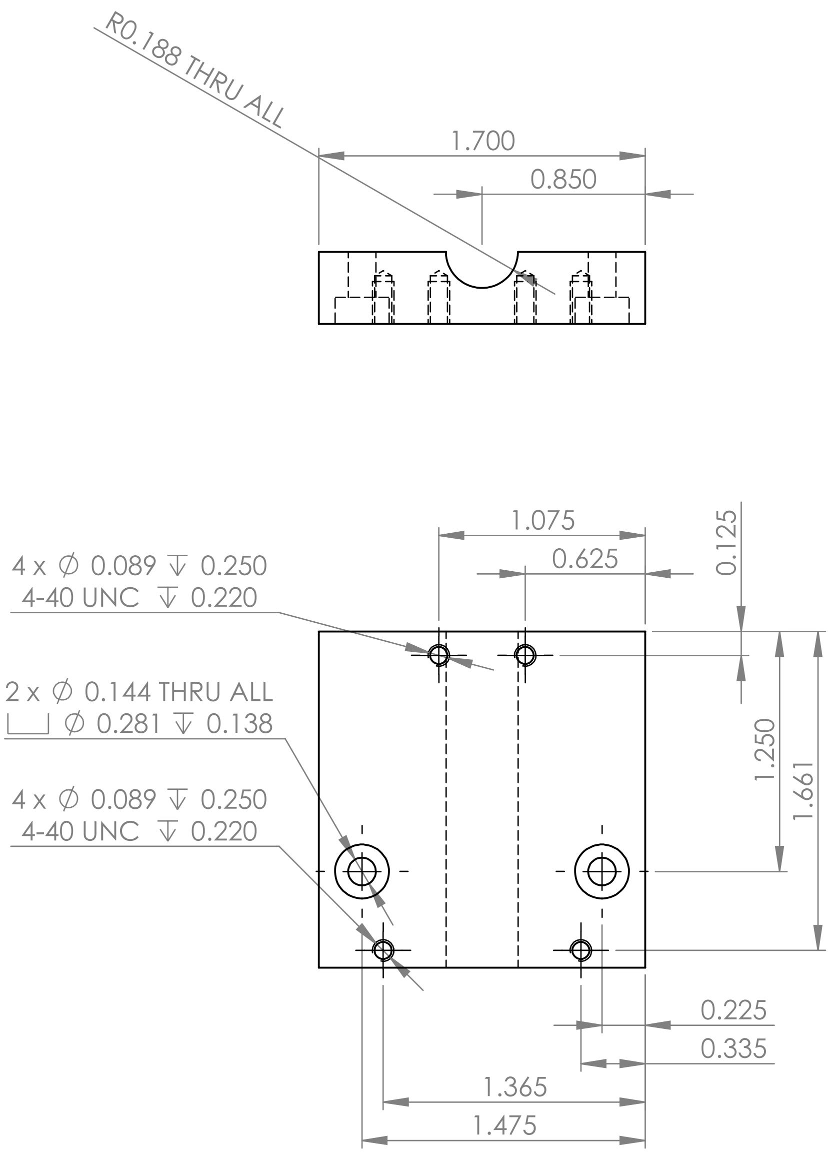

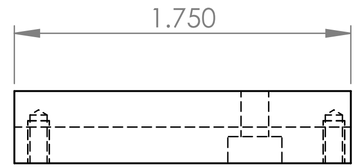

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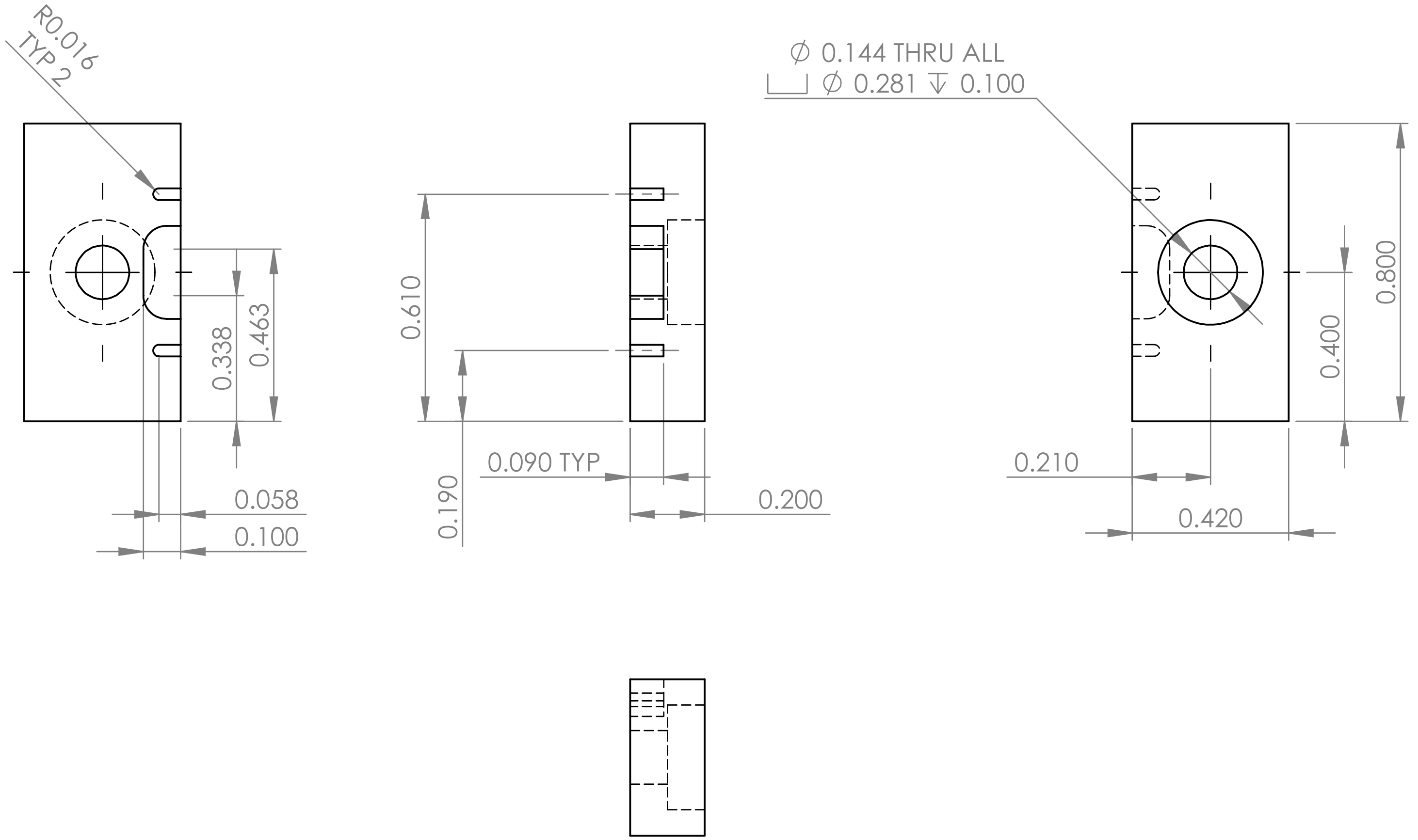

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	MFG APPR.		
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MATERIAL Nylon 6-10	COMMENTS:		
FINISH Mill			
DO NOT SCALE DRAWING			

AutoSut

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Gearbox Bracket

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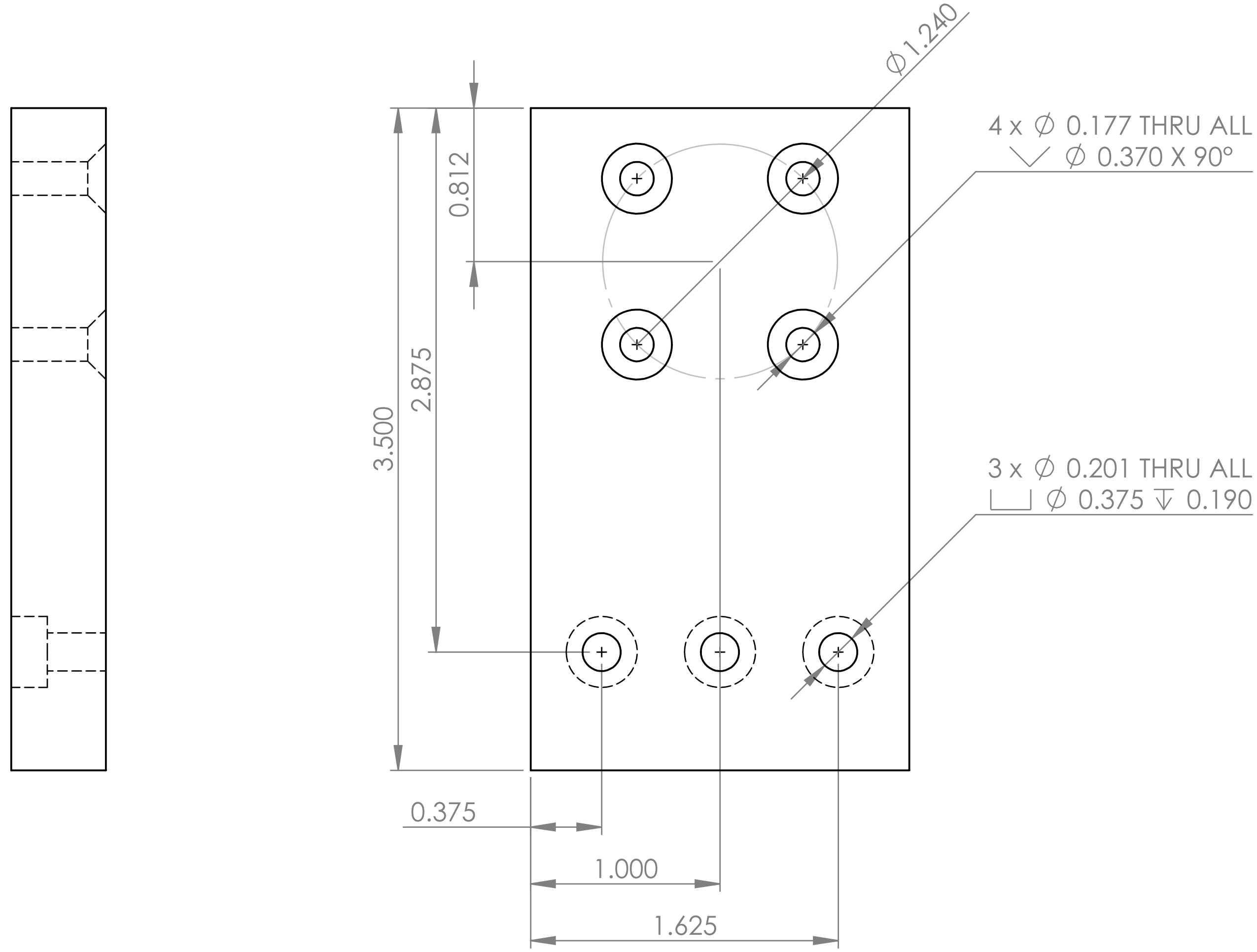

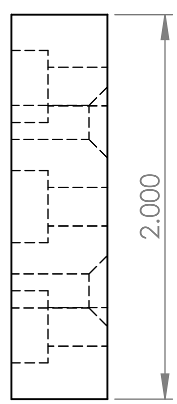

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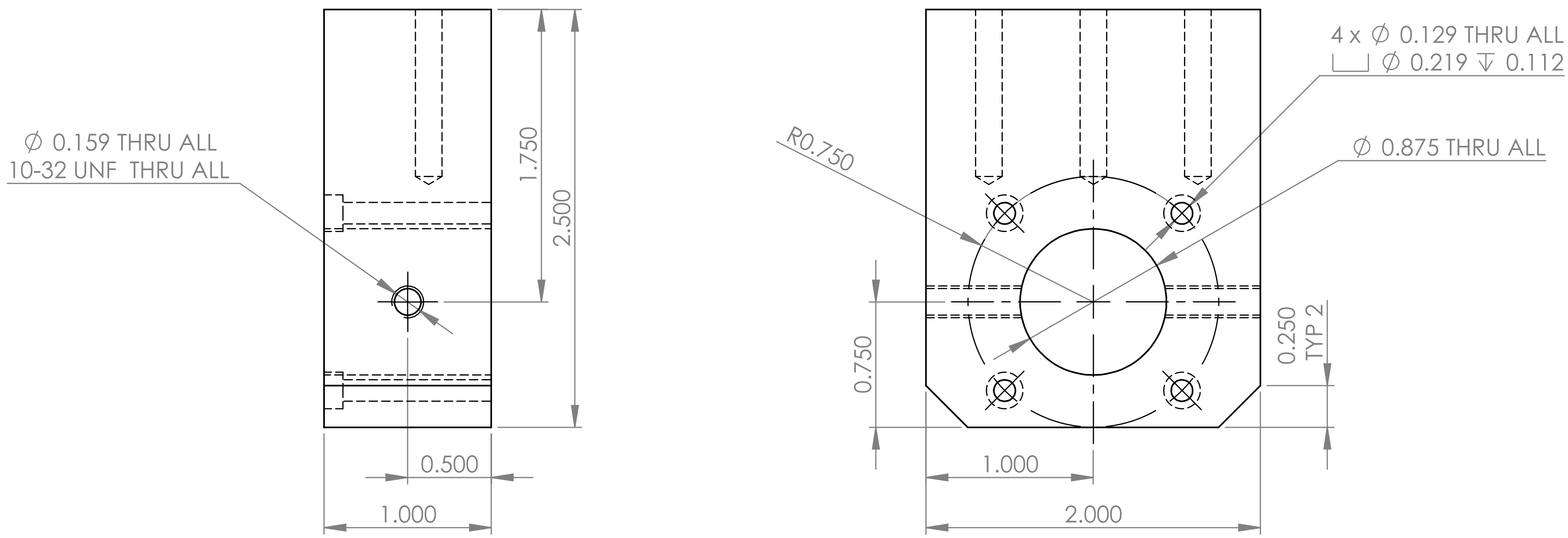

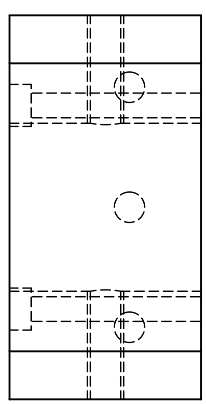

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TWO PLACE DECIMAL ± 0.010
THREE PLACE DECIMAL ± 0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL Nylon

FINISH Mill

DO NOT SCALE DRAWING

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DRAWN	BK	04/2013
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

AutoSut

TITLE:

Mount Base

SIZE A | DWG. NO. 1 | REV 1

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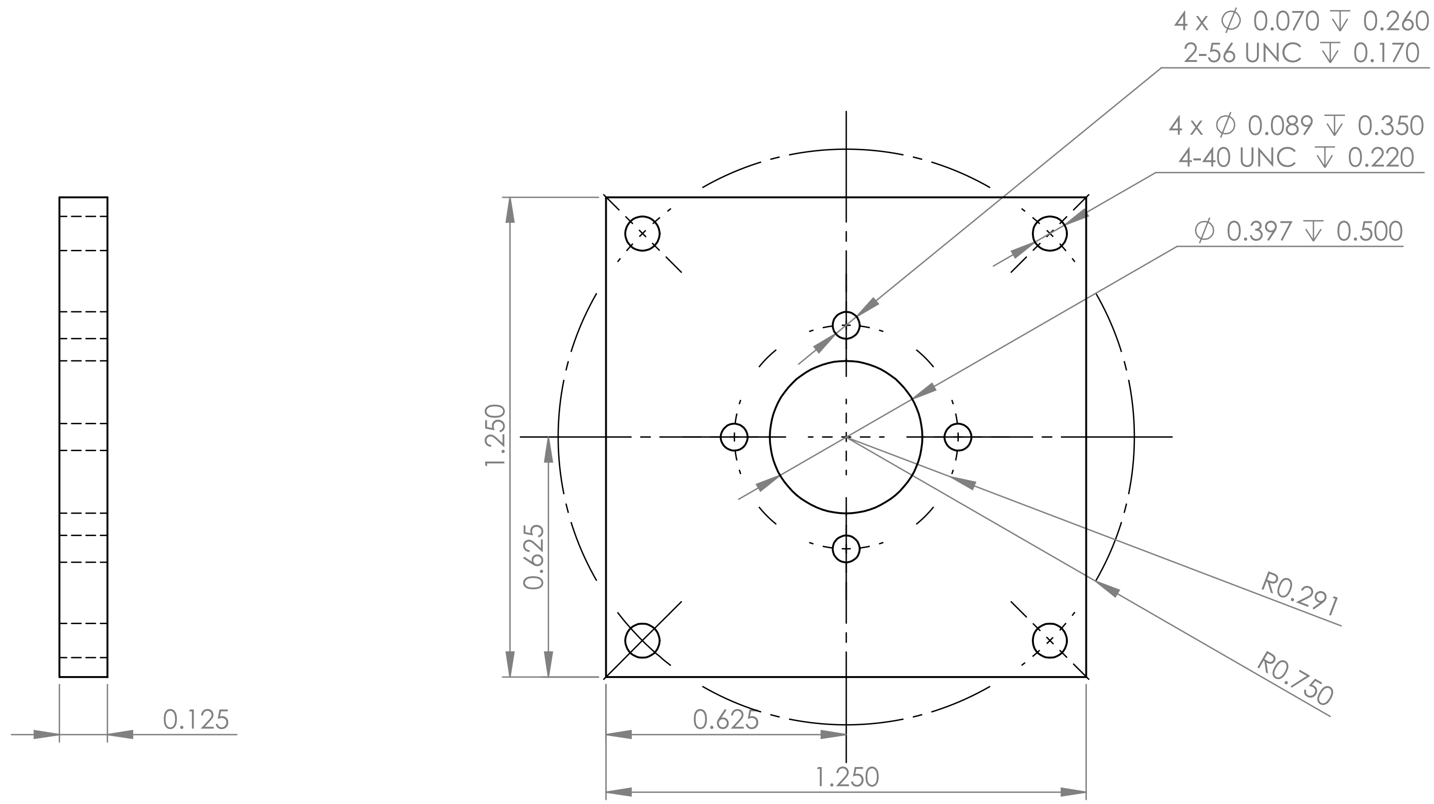

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FINISH Mill				
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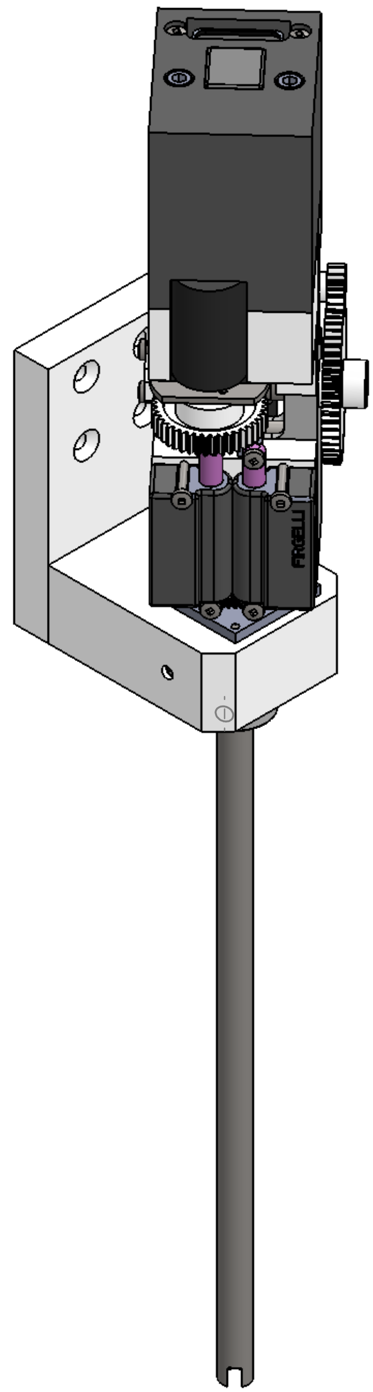
5 4 3 2 1

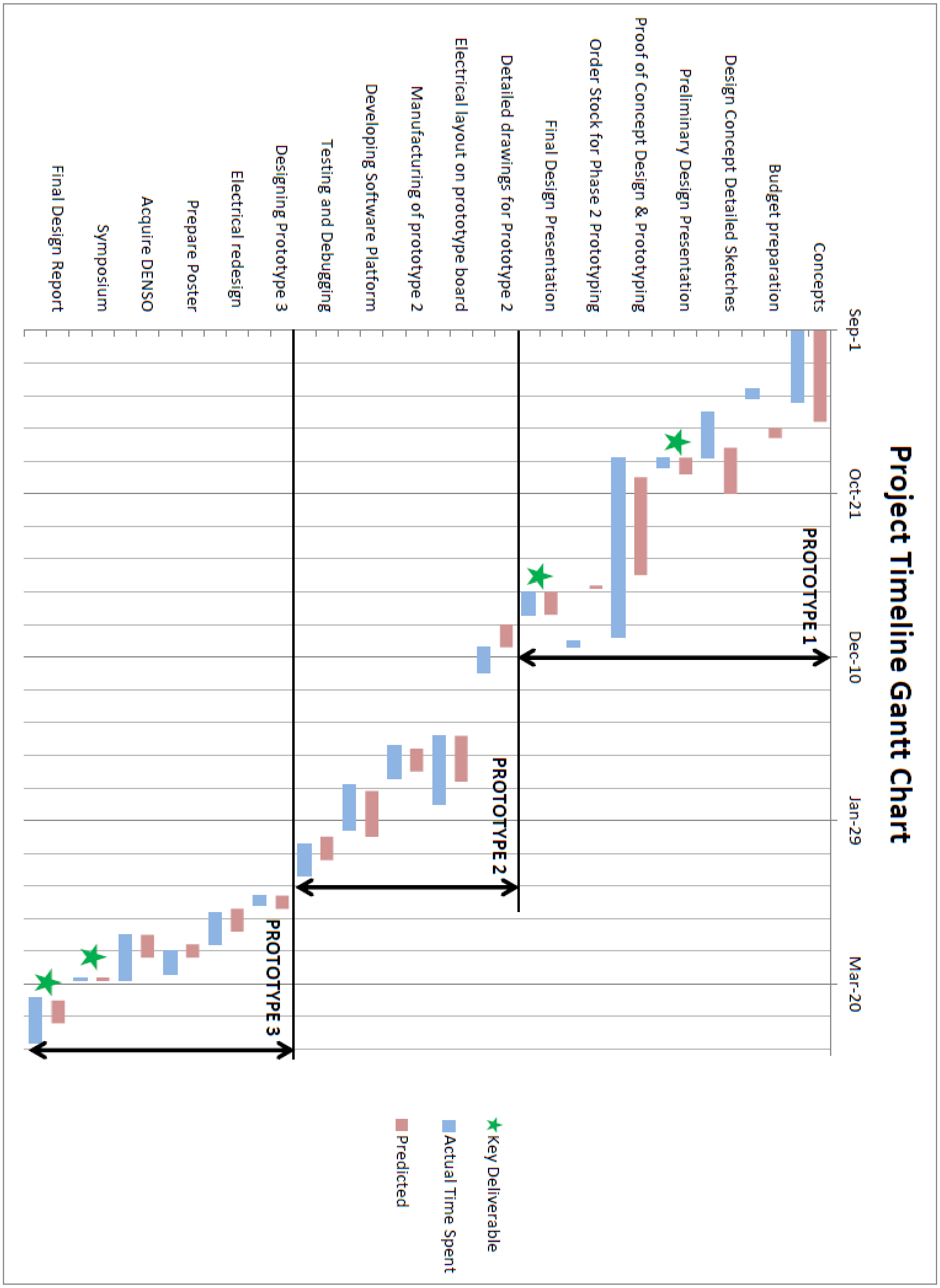
8 APPENDIX II : BILL OF MATERIALS

ITEM NO.	CAD MODEL NAME	QTY.
1	DensoMount_Plate	1
2	OuterRoll_Base	1
3	MOD_gear_sdpi_s1268z-048a040	1
4	collar_mc_60475K680	1
5	OuterRoll_gearPlate	1
6	ball_bearing_mc_6383K160	2
7	washer_mc_93785A700	1
8	FlatScrew_2-56x0250	4
9	CapScrew_10-32x1250	3
10	CapScrew_4-40x1000	4
11	Set_10-32x0750	2
12	EnclosureBottom	1
13	Pitch_GuideBar	1
14	GearboxBracket	2
15	Screw_4-40x0375	8
16	PanScrew_6-32x0375	2
17	PanScrew_6-32x1250	2
18	JawShaft	1
19	Gearbox	1
20	gearboxGear_m07t16	1
21	NeedleControlRod	2
22	Needle_Coupler	2
23	ssToolShaft	1
24	Nut_2-56	2
25	L12_linAct_Body	1
26	Gripper_thrustFitting	1
27	stepper_motor_20mm_DK_P14334-ND	3
28	EnclosureCap	1
29	EncoderMounting	2
30	RotaryEncoder_237T	3
31	gear_m07-42_a-1m-2myz07042	1
32	Set_4-40x0125	7
33	Screw_4-40x0500	2
34	gear_p32-14_SPD-A1T2-Y32014	1
35	Pitch_Shaft	1
36	Pitch_Spool	2
37	Ball_Bearing_AXA1221	2
38	Pitch_Collar	1
39	gear_p32-52_SPD-S1084Z-032DS052	1
40	Pitch_GearSpacer	1
41	Needle_Block	1
42	pq-12-20_closed1	2
43	LinActSpacer	2
44	CapScrew_6-32x0500	2
45	Screw_4-40x0625	2
46	Screw_4-40x0750	2
47	gear_sdpi_s1063z-048a040	1
48	Screw_4-40x0250	2
49	WireCap	1
50	hdmi_WM5715-ND	1
51	CapScrew_8-32x2250	2



9 APPENDIX III : GANTT CHART

The following figure depicts the anticipated and actual timelines for the duration of the project.



10 APPENDIX IV : DETAILED BUDGET

The subsequent 6 pages includes a detailed budget for the expenses for the project. The purchases are divided into three categories: mechanical, electronics, and miscellaneous expenses.

Supplier	Parts	#	$/ea	Total	Tax	Shipping	Total	Category
3D Print Center								
37	Printed Cap	1	$ 15.61	$ 15.61				
				$ 15.61	$ 2.03	$ -	**$ 17.64**	Mechanical
Adafruit								
219158	Boarduino	1	$ 17.50	$ 17.50				
	Prototype Boards	1	$ 19.95	$ 19.95				
	USB FTDI TTL-232 Cable	1	$ 20.00	$ 20.00				
				$ 57.45	$ 0.86	$ 7.50	**$ 65.81**	Electronics
Amazon								
701-9657207	Pelican Case	1	$ 234.85	$ 234.85				
				$ 234.85	$ -	$ 17.95	**$ 252.80**	Miscellaneous
Commercial Solutions Inc								
992400	Bearings	2	$ 4.62	$ 9.24				
				$ 9.24	$ 1.20	$ -	**$ 10.44**	Mechanical
DigiKey								
40567088	Prototype Board	2	$ 6.17	$ 12.34				
	Cable 6-wire	1	$ 2.96	$ 2.96				
	Connectors - 6pos header	8	$ 1.12	$ 8.96				
	Connectors - 6pos receptor	8	$ 2.32	$ 18.56				
	Connectors - 4pos header	5	$ 1.26	$ 6.30				
	Connectors - 4pos receptor	5	$ 1.26	$ 6.31				
				$ 55.43	$ 8.25	$ 8.00	**$ 71.68**	Electronics
35085544	Rotary Sensors	5	$ 2.86	$ 14.30				
	Rocker Switch	2	$ 0.69	$ 1.38				
	Trimmers	10	$ 0.92	$ 9.20				
	MUX	6	$ 0.63	$ 3.78				

	IC Socket	4	$	0.85	$ 3.40					
					$ 32.06	$	5.21	$ 8.00	**$ 45.27**	Electronics
35626964	DVI Cable	1	$	19.07	$ 19.07					
	USB adapter cable	1	$	2.58	$ 2.58					
	Rotary Sensors	5	$	2.95	$ 14.75					
	USB-FTDI cable	1	$	22.20	$ 22.20					
					$ 58.60	$	8.66	$ 8.00	**$ 75.26**	Electronics
34499279	DC Motors	4	$	39.68	$ 158.72					
	BreadBoard	1	$	9.78	$ 9.78					
	Power Supply	1	$	32.59	$ 32.59					
	Power Conn Jack	1	$	2.28	$ 2.28					
	Power Conn Jack	1	$	0.98	$ 0.98					
	Voltage Regulators	6	$	1.84	$ 11.04					
					$ 215.39	$	10.32	$ 17.68	**$ 243.39**	Electronics
40966518	Stepper Motors	4	$	41.95	$ 167.80					
					$ 167.80	$	21.81	$ -	**$ 189.61**	Electronics
45363373	Voltage Regulators	4	$	1.88	$ 7.52					
	USB A - USB B adapter	1	$	8.26	$ 8.26					
	90* angled header 6pos	1	$	1.35	$ 1.35					
	Cable Grip	1	$	2.88	$ 2.88					
	Conn receptor 8pos	7	$	1.55	$ 10.85					
	Conn female headers 12pos	3	$	1.08	$ 3.24					
	Conn receptor 15pos	2	$	1.64	$ 3.28					
	Conn female header 6pos	1	$	0.75	$ 0.75					
	Conn female header 10pos	3	$	0.96	$ 2.88					
	Conn female header 4pos	1	$	0.64	$ 0.64					
	Conn female header 2pos	3	$	0.53	$ 1.59					
	Power jack connector	1	$	2.02	$ 2.02					
	Breakaway header	14	$	1.02	$ 14.24					
	Terminal block	3	$	1.06	$ 3.18					

	Cable 10wire	1	$ 3.72	$ 3.72						
	Power cable	1	$ 3.88	$ 3.88						
				$ 70.10	$ 10.15	$ 8.00	**$ 88.25**			Electronics
DipMicro										
130120-160€	Atmega328	5	$ 17.86	$ 17.86						
				$ 17.86	$ 2.33	$ 8.00	**$ 28.19**			Electronics
EBAY										
1Y014719E3	Pinion Gear	1	$ 3.46	$ 3.46						
				$ 3.46	$ -	$ 5.00		**$ 8.46**		Mechanical
Engineering Machine Shop										
	Drill Rod	1	$ 4.53	$ 3.76						
	Fasteners	20	$ 0.06	$ 1.20						
	Aluminum Shaft	1	$ 0.46	$ 0.38						
	5mm Drill Rod	1	$ 11.20	$ 5.60						
	1x2 Alum f/bar	1	$ 8.83	$ 4.42						
	1/8 Drill Rod	1	$ 1.01	$ 1.01						
	Miscellaneous	1	$ 3.00	$ 3.00						
	Plastic	1	$ 7.80	$ 7.80						
	Unknown	1	$ 8.13	$ 8.13						
				$ 35.30	$ 4.59	$ -		**$ 37.82**		Mechanical
GoDaddy										
516458880	Website	1	$ 25.33	$ 25.33						
				$ 25.33	$ 3.29	$ -			**$ 28.62**	Miscellaneous
James 3D Printing										
	Conduit (custom)	1	$ 5.00	$ 5.00						
	Gear (custom)	1	$ 2.00	$ 2.00						
	Cap	1	$ 10.00	$ 10.00						

					$ 17.00	$ -	$ -	**$ 17.00**	Mechanical
McMaster-Carr									
40580100	Spur Gear	4	$ 3.25	$ 13.00					
	Timing Belt	2	$ 2.93	$ 5.86					
	Belt Pulley	1	$ 7.61	$ 7.61					
					$ 26.47	$ 2.50	$ 12.67	**$ 41.64**	Mechanical
46188218	Nylon 1-1/4" thick, 2" wide	2	$ 29.91	$ 59.82					
	Nylon fasteners 6-32	1	$ 5.79	$ 5.79					
	Nylon fasteners 4-40	1	$ 5.53	$ 5.53					
	Nylon spacer	1	$ 6.20	$ 6.20					
	PTFE Washer	1	$ 3.61	$ 3.61					
	Set screw collar 10mm bore	3	$ 1.81	$ 5.43					
	Set screw collar 5mm bore	1	$ 1.48	$ 1.48					
	Set screws 4-40	1	$ 6.20	$ 6.20					
	Teflon rod 3/16" dia	1	$ 1.65	$ 1.65					
	Nylon 1/2" thick, 2" wide	1	$ 14.39	$ 14.39					
	Hex Standoffs	8	$ 0.44	$ 3.52					
	Nylon cable tie	1	$ 2.27	$ 2.27					
	18-8 Machine screws	1	$ 7.61	$ 7.61					
	Heat-shrink tubing	1	$ 35.80	$ 35.80					
	Carbide-tipped drill bit	1	$ 11.42	$ 11.42					
	Steel ball bearing	3	$ 6.59	$ 19.77					
					$ 190.49	$ 9.52	$ 13.08	**$ 213.09**	Mechanical
47180451	Steel ball bearing	3	$ 4.41	$ 13.23					
	PTFE Sleeve bearing	2	$ 5.01	$ 10.02					
	Steel tubing	1	$ 6.11	$ 6.11					
	Aluminum tubing	1	$ 6.25	$ 6.25					
	Nylon set screw shaft collar	2	$ 2.75	$ 5.50					
	Nylon screw 8-32	1	$ 6.90	$ 6.90					
	Nylon 1/2" thick, 2" wide	1	$ 14.39	$ 14.39					
	Brass tubing	1	$ 4.72	$ 4.72					

	Steel machine screw 2-56	1	$ 2.88	$ 2.88					
	Steel cap screws 4-40	1	$ 3.79	$ 3.79					
	Brass spacers	4	$ 1.14	$ 4.56					
	Stainless steel spacers	1	$ 1.73	$ 1.73					
	Nylon spacer	1	$ 1.19	$ 1.19					
				$ 81.27	$ 4.08	$ 12.46		**$ 97.81**	Mechanical
Omnimodels									
600660	Pinion Gear	1	$ 4.09	$ 4.09					
	Axial Bearing	2	$ 4.89	$ 9.78					
	Axial Pinion Gear	2	$ 5.99	$ 11.98					
	Axial Spur Gear	1	$ 23.59	$ 23.59					
				$ 49.44	$ -	$ 22.99		**$ 72.43**	Mechanical
RobotShop									
279497	Atmega 328	1	$ 5.50	$ 5.50					
	Stepper Motor Driver	5	$ 12.95	$ 64.75					
				$ 70.25	$ 9.95	$ 6.29	**$ 86.49**		Electronics
278410	L12 Linear Actuator	2	$ 80.00	$ 160.00					
	Breakaway Female Headers	5	$ 1.50	$ 7.50					
	DC Motor Driver	2	$ 17.95	$ 35.90					
				$ 203.40	$ 27.23	$ 6.08	**$ 236.71**		Electronics
283411	Emergency Stop	1	$ 19.73	$ 19.73					
				$ 19.73	$ 3.38	$ 6.26	**$ 29.37**		Electronics
268065	Stepper Motor Driver	4	$ 12.95	$ 51.80					
	DC Motor Driver	2	$ 17.95	$ 35.90					
	Linear Actuator	1	$ 80.00	$ 80.00					
	Arduino Uno	1	$ 28.99	$ 28.99					
				$ 196.69	$ 26.37	$ 6.15	**$ 229.21**		Electronics

287366	DC Motor Drivers	3	$ 17.95	$ 53.85						
	Boarduino	1	$ 25.00	$ 25.00						
	Stepper Motor Driver	1	$ 9.95	$ 9.95						
				$ 88.80	$ 14.98	$ 26.46	**$ 130.24**			Electronics
Sanction										
	Roller Bearings	1	$ 11.99	$ 11.99						
				$ 11.99	$ 1.56	$ -		**$ 13.55**		Mechanical
Sayal										
	Prototyping Equipment	1	$ 65.00	$ 65.00						
	Final PCB Parts	1	$ 101.00	$ 101.00						
				$ 166.00	$ -	$ -	**$ 166.00**			Electronics
SDP-SI										
C1302S1290	Acetal 32dia. Pitch, N52	2	$ 22.96	$ 45.92						
	Aluminum 48dia. Pitch, N40	2	$ 13.43	$ 26.86						
	Aluminum 48dia. Pitch, N40	2	$ 11.33	$ 22.66						
	Acetal 0.70module, N42	3	$ 3.22	$ 9.66						
	Acetal 0.70module, N42	2	$ 4.30	$ 8.60						
				$ 113.70	$ 16.45	$ 3.95		**$ 134.10**		Mechanical
UPS										
	Brokerage Fee	1	$ 54.88	$ 54.88						
				$ 54.88	$ -	$ -			**$ 54.88**	
					Taxes	Shipping	**Elec.**	**Mech.**	**Misc.**	
Subtotals					**$ 194.72**	**$ 204.52**	**$ 1,685.48**	**$ 663.98**	**$ 336.30**	
Total										**$ 2,685.76**

11 Appendix V: User Reference Manual

11.1 Replacement Part Numbers

Suppliers, part-numbers and any additional information needed to locate and re-order key electrical parts from the project are presented in the following table.

TABLE 5 - ELECTRICAL COMPONENT OVERVIEW

Part	# Parts	Supplier	Part Number	Additional Notes
Microcontroller	1	Adafruit	“Boarduino”	
Stepper Controller	3	Robotshop	RB-Pol-176	Pololu A4988 breakout board
H-Bridge (Linear actuator controllers	3	Robotshop	RB-Pol-109	Pololu MC33926 Breakout Board
Power Supply	1	Sayal	n/a	12V, 4A
Stepper Motor	3	Digikey	PG20L-D20-HHC0	
Linear Actuator (Small)	2	Robotshop	RB-Fir-44	Firgelli PQ12, 20mm, 100:1
Linear Actuator (Grip)	1	Robotshop	RB-Fir-26	Firgelli L12 30mm 210:1 12V
Rotary Encoders	3	Digikey	3382H-1-103-ND	Continuous

11.2 Printed Circuit Board

Below is an image of the PCB with the main components identified. Should any of the components need replacement, consult Table 5 to find the part number and simply remove the component in question from the board and insert the new one in the indicated location.

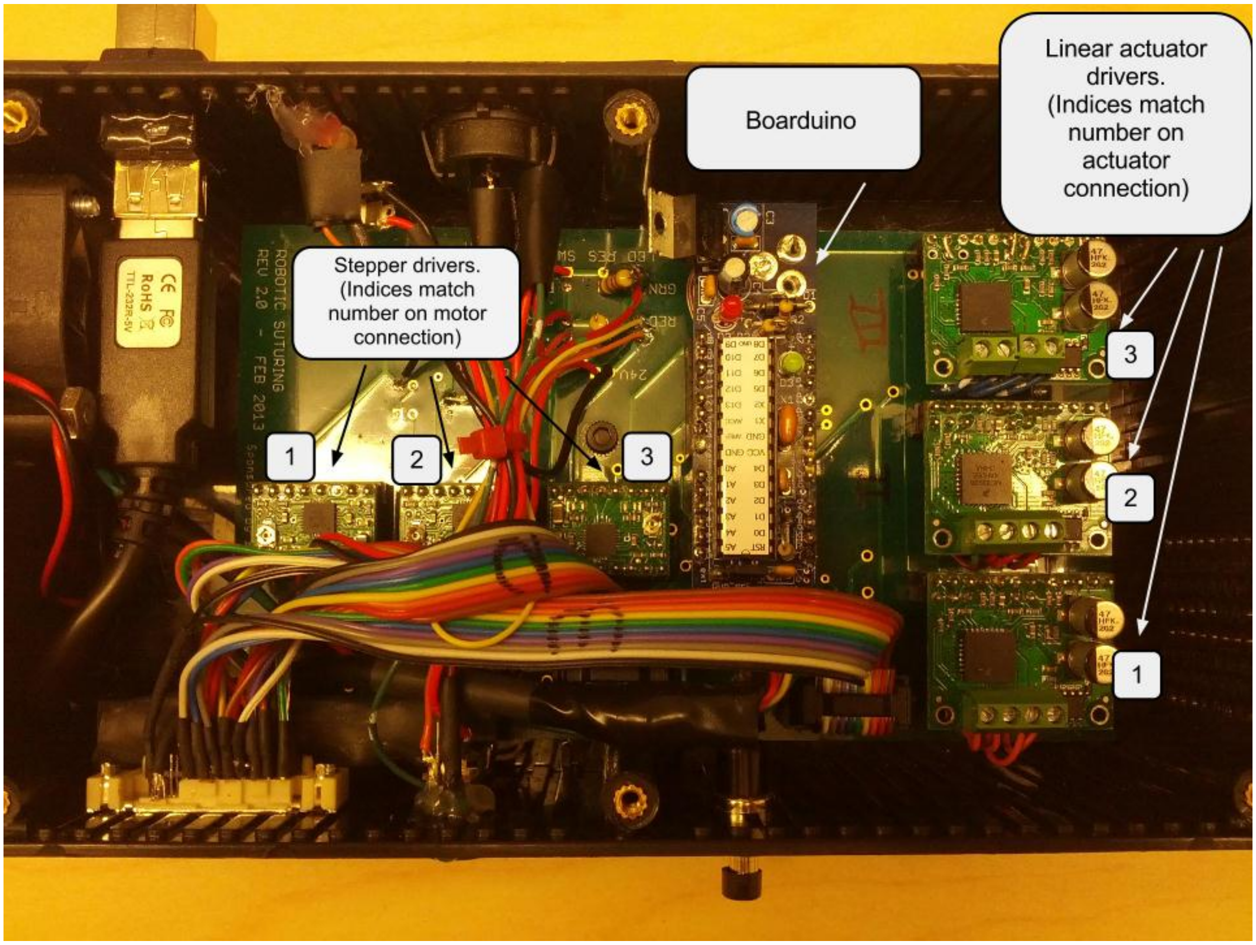


FIGURE 17 - PRINTED CIRCUIT BOARD WITH LABELLED COMPONENTS

11.3 ELECTRICAL CONNECTIONS

Consult the following diagrams for the standard connections to/from power, the computer and the robot.

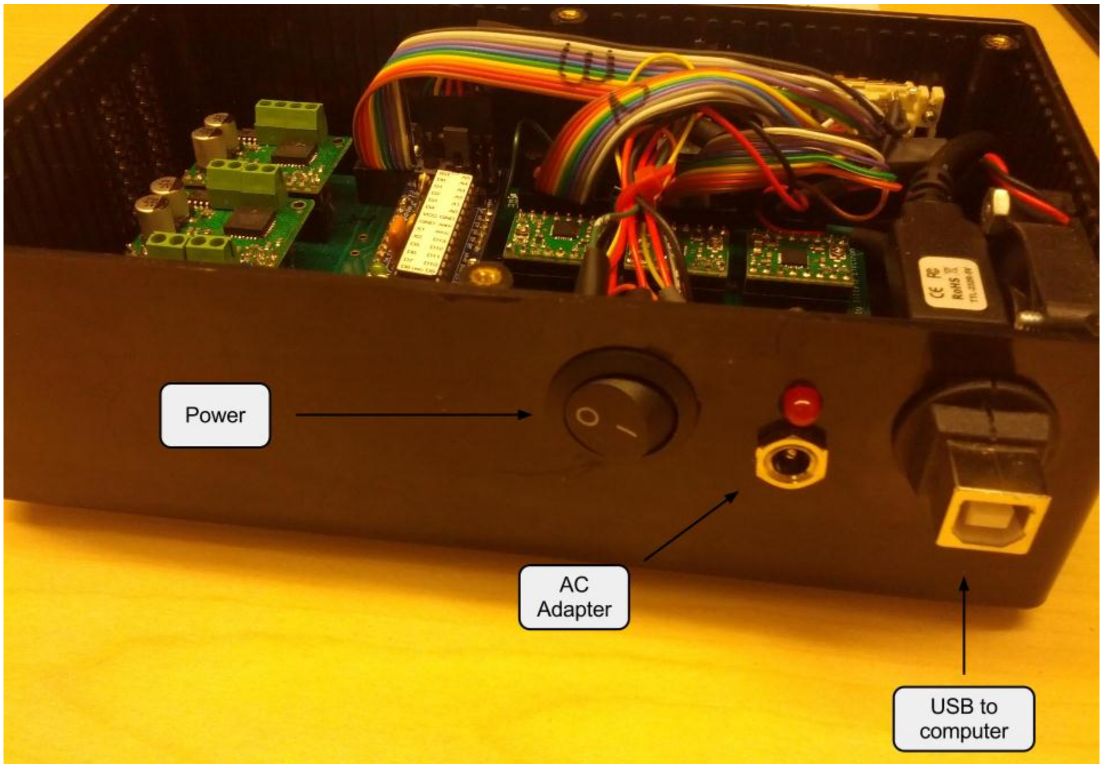


FIGURE 18 - CONNECTIONS TO THE ELECTRONICS BOX (FRONT)

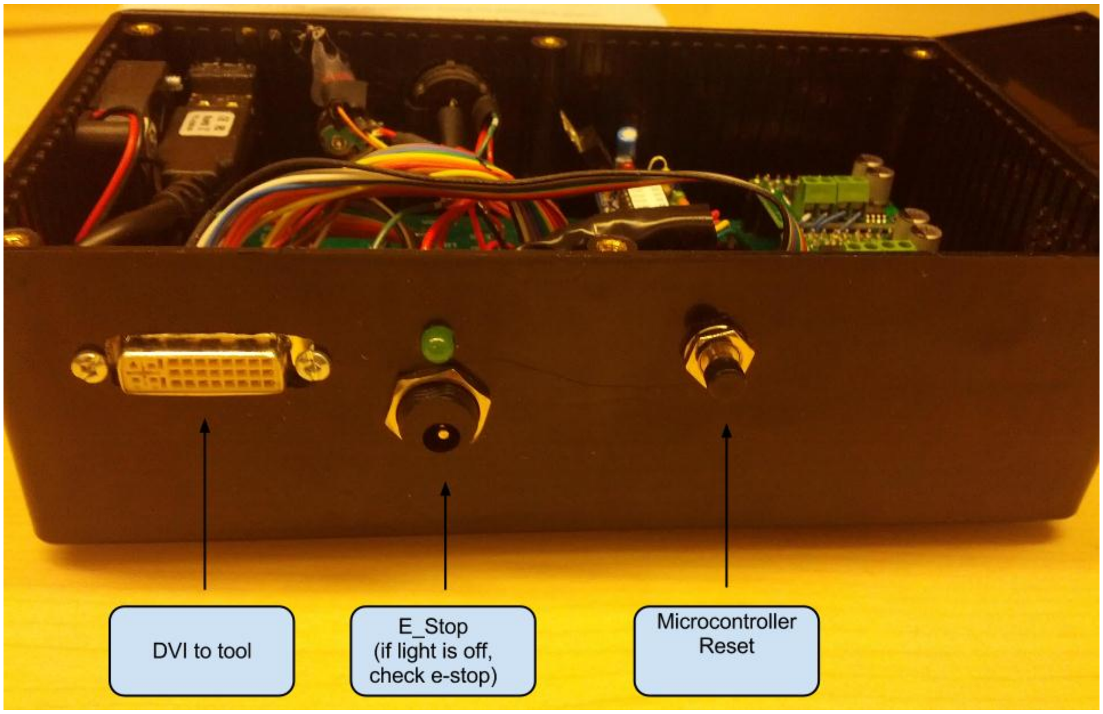


FIGURE 19 - CONNECTIONS TO THE ELECTRONICS BOX (BACK)

11.4 Software - Serial API

A multi-character menu offers an easy-to-use interface to control each of the actuators. The acceptable user commands are tabulated below. Each input parameter must be delimited by commas and the command must be terminated by a newline character. For example, a command to move the body roll by 10° clockwise would be “`OR, +D, 10 \n`”.

A general move command is composed of <function>, <direction><unit>, <value>. Units are sometimes optional.

To receive feedback from the robot, a simple “`E \n`” command is used.

TABLE 6 - USER COMMANDS FOR THE SERIAL INTERFACE

Input1: Function	Input 2: Option (direction, unit)	Input 3: Value	Notes
`P`: Move pitch	`D`: Move in degrees	#	• Desired angle must be between 5° and 75° • Direction will be chosen based on relative position of current and desired angles • If `D` is not specified, values will be interpreted as bit values • Example: “`P, D, 10 \n`"
`WR`: Move wrist roll	`+/-`: Move CW(+) or CCW(-) `D`: Move in degrees	#	• Direction must be specified • If `D` is not specified, values will be interpreted as bit values • Example: “`WR, -D, 15 \n`"
`OR`: Move outer (body) roll	`+/-`: Move CW(+) or CCW(-) `D`: Move in degrees	#	• Direction must be specified • If `D` is not specified, values will be interpreted as bit values • Example: “`OR, +D, 20 \n`"
`G`: Toggle grip	`C/O`: Close (C) or open (O) grip	n/a	• Example: “`G, C \n`"
`N`: Needle actions	`T/D`: Toggle needle (T) or drop needle (D)	n/a	• See section 11.4.1 • Example: “`N, T \n`"
`C`: Check state	`P`: Get pitch position (degrees) `W`: Get wrist roll position (degrees) `O`: Get outer roll position (degrees) `G`: Get gripper position (open(1) or closed(2)) `N`: Get needle position (in toggle arm 1(1) or in toggle arm 2(2)) `A`: Get all roll positions (pitch, outer roll, wrist roll) (degrees)	n/a	• Provides the current position of the specified linear actuator or stepper motor • Prints -1 if an invalid option is provided • Example: “`C, A \n`"

11.4.1 Needle Actions

The procedure to complete the available needle actions are explained below, including initial states.

- **Toggle needle:** The initial state required for a needle toggle is gripper closed. After running the `N,T` command, the user must open the gripper with `G,O`.

- **Drop needle:** The initial state required for a needle drop is gripper closed. The `N,D` command will drop the needle and open the gripper.

- **Load needle:** There is no command to perform an automated needle load since it is a multi-step process and it was determined that user input at each step would be beneficial in case of any error. A needle load may still be easily performed using the following commands:
  - `G,C` to close the gripper for the next step
  - `N,D` to "drop" the needle. This disengages both jaws from the needle and opens the gripper
  - `G,C` to close the gripper again
  - `N,T` to toggle the needle. After this one jaw will have the needle engaged
  - `G,O` to open the gripper

11.5 Software – GUI

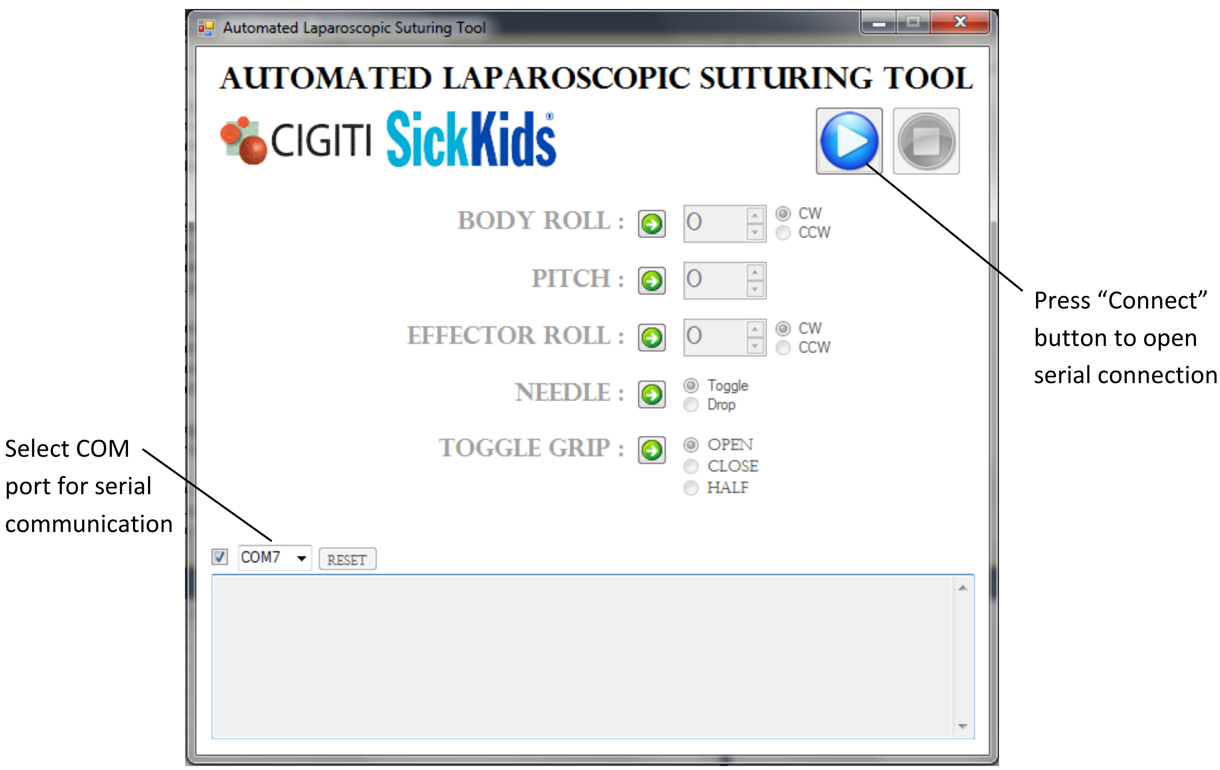


FIGURE 20 - WELCOME SCREEN

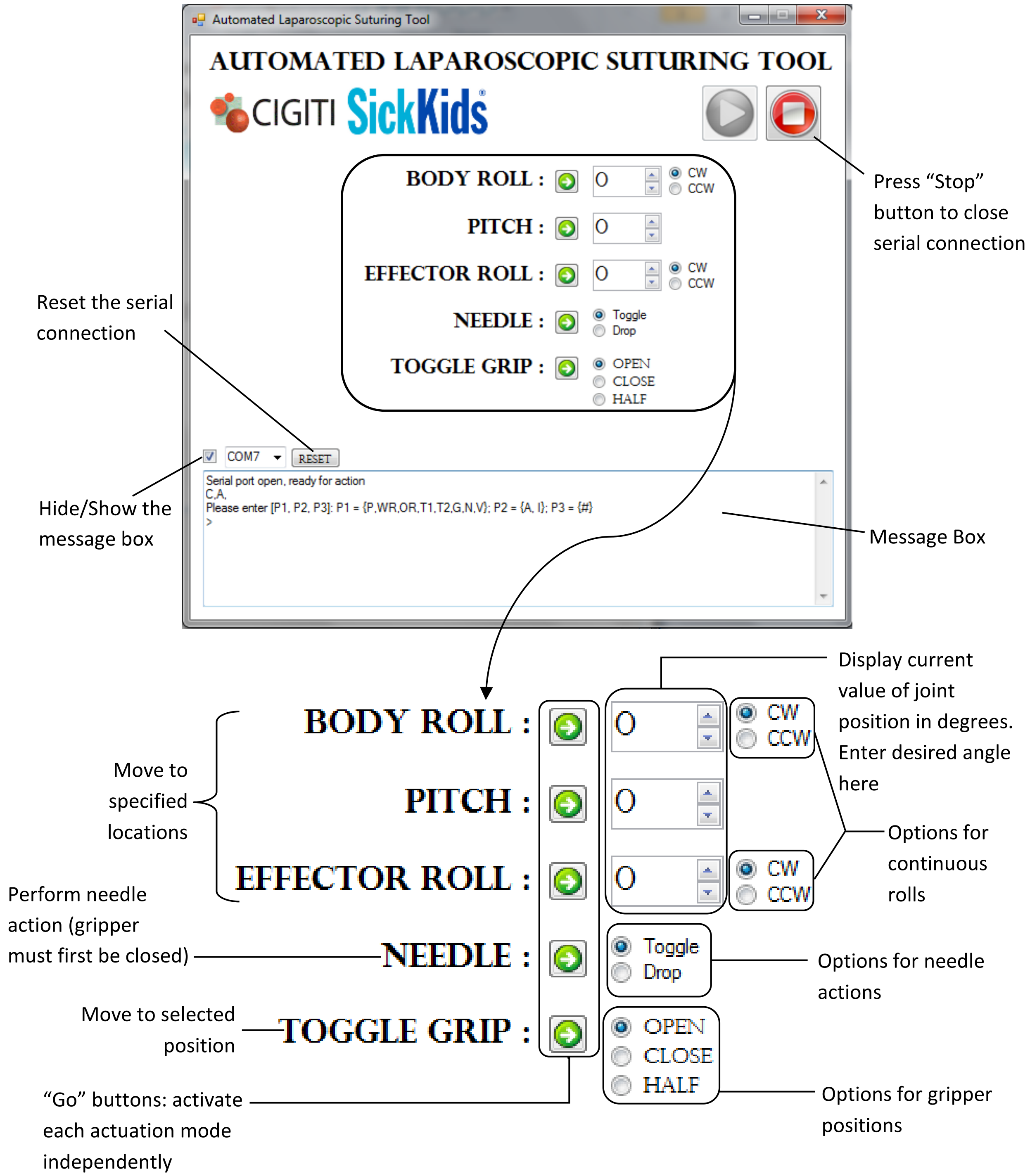


FIGURE 21 - EXPLANATION OF THE ACTIVE GUI

11.6 Using the Aluminum Prototype (Prototype 2)

The aluminum prototype does not connect to the driver circuits through a DVI cable. Three cables come from the tool. They are labeled 1, 2, and 3, and attach to the ten-pin connectors on the circuit board in the appropriately labeled connector. The top of the electrical box will need to be removed in order to access these connectors.