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Dear Professors,

This final design report was prepared as the culminating task for MTE481, the Mechatronics Engineering Design project course. The Mechatronics Engineering Design Project is the capstone project in the University of Waterloo Mechatronics Engineering Program, offering an opportunity to showcase the technical expertise and engineering competency acquired through completion of the program, through a creative medium of an open-ended design project. The purpose of this report is to discuss the progress through the initial design stages of this group's project.

This group has decided upon a Mechatronics design project in the biomedical field. The project will be completed in conjunction with the Centre for Image Guided Innovation and Therapeutic Intervention (CIGITI) at the Toronto Hospital for Sick Children. The design project discussed herein focuses on the development of an automated laparoscopic suturing tool which is to be used in a larger, cutting-edge research project being conducted by CIGITI. Entitled "KidsArm," the encompassing project aims to develop an automated surgical suite with the specific application of paediatric surgeries.

This report was written wholly by the authors listed below and has not received any previous academic credit at this or any other institution. The group would like to thank Prof. Huissoon for the continued guidance throughout the course of the term. Further, special acknowledgements must be made to the members of the CIGITI research group, who have not only provided the opportunity to be a part of such an exciting, cutting edge project, but are offering both financial and industrial support and have already donated major components for the design.

Sincerely,

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

# DESIGN OF A LAPAROSCOPIC SUTURING TOOL

## MTE 481: FINAL DESIGN REPORT

DECEMBER 3, 2012

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GROUP 11

# Executive Summary

The 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. In conjunction with CIGITI, the project has been defined as the development of an automated tool, ultimately capable of performing automated laparoscopic suturing as part of CIGITI's *KidsArm*. While this project involves the mechanical, electrical, 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 separately.

After considering the defined project criteria and constraints, it was determined that automating an existing tool was the most logical course of action. Designing a completely new tool would have been complex, time consuming, and would exceed the resources of the current project. As a result, the Covidien SILS™ Stitch tool was selected to be used as a mechanical platform for the project. This tool was determined to be the simplest tool to automate, namely since it offered all required functionality in a single tool. While other alternatives would have required a second manipulator at the surgical site to handle the tissue, the SILS Stitch's ability to pass a needle between two gripper jaws allows it to work independently of external assistance. While this did not affect the narrow scope of this project, it will ultimately simplify the automation process to be performed by CIGITI.

With a platform selected, two design alternatives were identified. The first would wrap around the existing tool and be capable of actuating all of the tool's degrees of freedom (DOFs) without physically modifying the tool. This would allow for an industry standard tool to be used for clinical trials, and would leverage the reliable actuation design already calibrated by Covidien. The second alternative is to disassemble the existing tool in order to be able to actuate the tool's inner control surfaces. While the exterior of the tool is designed to be easily operated by a surgeon's hand, it offers few solid actuation interfaces for rotational or linear actuators. By disassembling the tool, the intent is to produce a design with higher actuator accuracy and reliability.

Since both of these designs offer significant advantages and disadvantages, both designs have moved to the prototyping stage in order to properly asses which design will ultimately yield the best design for the final tool. Each alternative solution has been designed with an effort to use common electrical and electromechanical components. Since the actuation requirements are very similar between designs, this will reduce costs associated with prototyping two separate tool designs. In both solutions, combinations of linear actuators and stepper motors have been used in order to achieve high accuracy movement while minimizing drivetrain weight. Geared power-trains have been used where appropriate to increase actuator power and precision.

While lessons will be learned from testing both designs, only one design will ultimately be chosen since the two design strategies are incompatible. While it may appear enticing to combine features from each design, a merge of the two solutions would most likely offer more complexity than benefits. With initial prototypes on schedule for completion by late December 2012, it is anticipated that a final design will be formalized by the New Year. The project is currently under budget with less than 40% of the group's $2600 budget spent to date. With most components purchased, all major foreseeable costs will be raw materials, and as such it is anticipated that the whole project will be completed on time and under-budget.

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# 1 INTRODUCTION

## 1.1 BACKGROUND

Laparoscopic surgery is a field of minimally invasive surgery focused on the abdominal region. In traditional open surgeries, surgeons have full access to the surgical site with both of their hands. In laparoscopic surgeries, long, thin tools access the surgical site through small incisions made in the patient's side. The surgeon views the surgical site through an endoscope, a small camera placed in the patient's body.

The difficulties associated with laparoscopic surgery when compared to traditional open surgery are numerous, including limited access to the surgical site, magnified hand tremors along the length of the tool, and reversed hand controls. For these reasons, surgical tasks that would otherwise be considered routine in an open surgical setting can be the most tedious and time consuming in a laparoscopic surgery. One such task is laparoscopic suturing.

The Centre for Image Guided Innovation and Therapeutic Intervention (CIGITI) at the Hospital for Sick Children in Toronto implements robotic solutions to improve all aspects of the surgical experience. The goal of the *KidsArm* project is to save costs in the operating room by automating repetitive, time consuming tasks. This automation will provide enhanced reliability and precision, as well as expedite the overall surgical procedure. Handling the needle to perform the suturing task is difficult under the additional constraints of a laparoscopic surgery, and this task has been identified as the first step in reducing operating room time needed by routine surgeries. Therefore the first benchmark performance of the *KidsArm* robot will be to automatically suture along a path with the aid of computer vision provided by a standard endoscope.

A standard 6-axis industrial robot, the DENSO VP6242 will serve as the base platform of the robot. A tool is needed to allow the robot to perform the suturing task. The goal of this report is to describe the process of designing this tool.

## 1.2 NEEDS ASSESSMENT

Minimally invasive surgeries are becoming more popular over open surgery due to their advantages for the patient. While it is more difficult to perform the surgery, the patient experiences less trauma and has a quicker recovery time. An improved experience for the patient is sufficient motivation to drive this research forward. The challenges inherent in the laparoscopic setup require extensive training for the surgeon. It takes lots of practice to become proficient with the reversed controls, magnification of hand tremors due to the ratio of the lengths of the tool shafts inside and outside the body, and limited access to the surgical site. Automation of this process can offer greater reliability and precision.

The need for this tool was expressed by the group's partner, the CIGITI research group, who is currently working on researching and developing a project that aims to perform completely automated surgeries. The first benchmark operation of CIGITI's surgical suite is automated, laparoscopic, vision-guided suturing. Suturing, or sewing up a wound, is the most time consuming task in a surgery. Automation of this process would offer significant time savings in the operation room, and correspondingly large reduction in financial costs of the surgery since the room, equipment and personnel will all be utilized more efficiently. Further, shorter operation times would have the potential to improve the throughput of the operation room.

The scope of this project consists of developing an automated tool with all the necessary actuation points and requisite feedback. The controls and integration of the tool with the 6-DOF robotic arm and the rest of the surgical suite will be the responsibility of CIGITI and will not be covered in this project. The need is for an automated laparoscopic suturing tool for use in minimally invasive surgeries that accepts control signals for different degrees of freedom, and receives feedback as to the execution of those commands.

## 1.3 Problem Formulation

**Problem Statement**

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

### 1.3.1 Objectives

The design should offer a modular solution for performing automated laparoscopic suturing. With a simple, easy-to-use interface, the final design should accept actuation position commands and use these to position the tool and successfully attach two ends of a lumen. Feedback regarding the tool's position and the status of the tissue binding should be returned by the tool. The reliability of successful binding should be maximized.

The tool is intended for minimally invasive surgeries, thus the tool should be able to operate through a trocar (a small surgical instrument acting as a compact gateway for tools to the inside of the body). As the tool will be mounted on a 6-DOF robotic arm in the CIGITI laboratory environment, the size of mounted tool should minimized so that when mounted on the arm, the robot can move freely without self-collision.

### 1.3.2 Constraints

The required design and performance parameters for the proposed design solutions are as follows

i. The weight of the tool shall not exceed 2.5 [kg]
ii. The cost of the final tool shall not exceed $1000
iii. The tool must fit through the trocar, thus the shaft diameter must be less than 10[mm]
iv. The tool must achieve high repeatability: joint accuracy to ±5$^{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

The key constraints are related to integration of the tool, namely the weight, size, repeatability and feedback offered. The tool must be able to move into the commanded position, and accurately track where it has moved.

### 1.3.3 Criteria

The attributes of the design that will serve as the basis for comparing proposed design solutions are

| | | |
|---|---|---|
| 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]

The most important criteria for selecting a design platform is ease of automation. When selecting proposed design solutions, the ease of manufacturing and reliability will be the critical criteria.

## 1.4 PATENTS

Existing patents have not been a major concern throughout the design phase of this project. That is because this project is being done in conjunction with a research group (CIGITI) to develop a proof-of-concept tool as part of their larger automated surgical suite. This tool will be used for lab testing and will never be commercialized. For that reason, issues such as the modification of an existing tool for use in the new design does not infringe on the original company's rights. Significant research was still put into finding related patents to determine if and how the project infringes on existing patents for either the end-effector (tip of the tool) or the control system.

Three very relevant end-effector patents were quickly discovered which related to the current design. These patents covered how laparoscopic tools were able to close wounds and fell into two main categories: stapling and suturing. The following wound closure technologies were considered for use in this project:

**Tissue Stapler (US 2006/00116989 A1)**

This patent shows the design for a tool capable of stapling tissue together in order to close a wound. This method of wound closure leaves metallic staples in the patient's body which could have a detrimental effect on patient acceptance of the new tool. While stapling tools are used in surgeries today, it was decided that this new tool should ideally move away from such technologies rather than continue to make use of them. Secondly, in order to staple the tissue closed, at least one other gripper tool would have to be used to hold the tissue closed while the staples were fired. Having a second tool at the remote surgical site could greatly complicate the process as precise coordination is difficult in a harsh environment with only optical sensors.

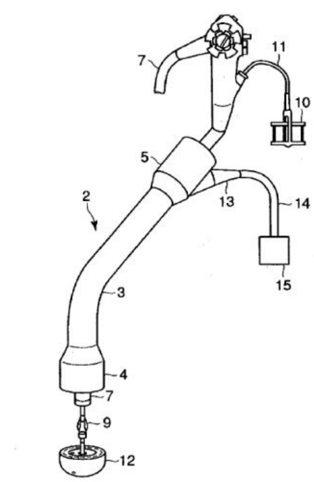


**FIGURE 1 - TISSUE STAPLER**

**Curved Needle (US 6,443,962 B1)**

Unlike the first patent, the curved needle patent uses suturing to close the wound. It does so by passing a needle shaped in an (approximately) 200$^{o}$ arc. Passed through a special channel in the tool, the needle is exposed for less than 180$^{o}$ of its arc. Due to the geometry of the needle and the tool, it is impossible to drop the needle from the tool. This, combined with the elimination of residual staples in the patient's body make the curved needle tool a much more attractive option then the tissue stapler. Unfortunately

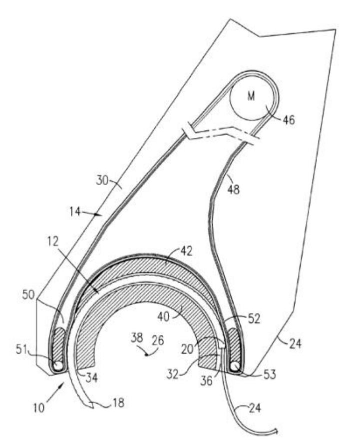


**FIGURE 2 - CURVED NEEDLE**

this tool still requires a second gripper tool to hold the tissue in place which for the reasons above prevented it from being an ideal solution.

**Endostitch Tool (US 8,177,794 B2)**

The third patent investigated was the Endostitch tool. This tool incorporates the needle passing mechanism into a gripper tool. This allows a single tool to both grasp the tissue and pass a needle through it without the need to coordinate with a second tool. The needle is simply passed from one jaw to the other for each piece of skin, making the process very discrete and (relatively) easier to plan and execute. No staples or residual material are left in the patient's body with the exception of a biodegradable thread.

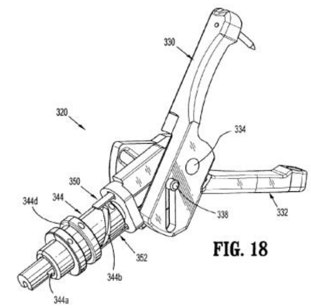



**FIGURE 3 - ENDOSTITCH**

After careful consideration, the Endostitch tool was selected as a platform on which to base the project for the reasons listed above.

# 2 PROPOSED SOLUTION

## 2.1 ABSTRACTION

The goal of the project is to create a tool that when mounted on a robotic arm will allow that robot to complete a suturing task along a given path.

In order to achieve this task, three main areas of connecting tissue were considered: tissue welding, stapling and suturing.

Tissue welding involves using glue or electrocautery to adhere the two tissue surfaces together. Various sources have shown tissue welding techniques to be successful in a laparoscopic environment. The design concepts that stemmed from this strategy all involved two arms to bring the pieces of tissue together before performing the welding procedure.

Stapling is a straightforward procedure where stainless steel or biodegradable staples are used to crimp the two pieces of tissue together. Doctors were asked whether leaving staples in the patient's body was problematic, and none of them considered it a disadvantage of using this technique. The only disadvantage associated with this strategy was that similar to the tissue welding designs, the stapling designs required two arms to bring the two pieces of tissue together before connecting them.

Suturing involves using a needle and thread to sew the two pieces of tissue together. Traditionally, a curved needle is used in laparoscopic suturing which allows the surgeon to pass the needle through any tissue geometry with a signal twist of their wrist. A selection of tools are available that are made to facilitate the process of laparoscopic suturing. It was quickly identified that if suturing would be the adhesion strategy chosen for this project, automating a tool designed to perform laparoscopic suturing would be the easiest way to achieve the project goals.

Two suturing tools were considered for the project mainly due to availability: the Covidien Endostitch and Covidien SILS Stitch.

Both tools use a straight needle to pierce the tissue. The tissue is clamped in the jaw of the tool and the needle is passed back and forth from one jaw to the other. The functionality is similar to that of a sewing machine. The Endostitch tool has the suturing head at the end of a rigid shaft. The suturing mechanism is shown in Figure 4.


**FIGURE 4 – END EFFECTOR OF THE COVIDIEN ENDOSTITCH TOOL (SOURCE: COVIDIEN)**

The SILS Stitch has the same suturing mechanism as the Endostitch, but offers two extra degrees of freedom to orient the end effector. This allows the robot more dexterity once it has entered the patient, and will make the suturing task easier to complete.

**FIGURE 5 - THE COVIDIEN 3 DOF SILS STITCH SUTURING TOOL (SOURCE: COVIDIEN)**

The weight limit constraint is considered in each stage of design and is the driving force behind most material and parts selection. Light plastics will be used for the structural members of the design, plastic gears and fasteners will be used wherever possible and plastic gear boxes on the motors will be used if they can be acquired.

## 2.2 PROPOSED SOLUTION SELECTED

After considering the various potential solutions, the platform selected for this project is the SILS Stitch tool. The primary reason for selecting the SILS Stitch is that it offers the simplest possibilities for ease of automation, one of the key constraints in selecting a design. This is one the only tools which would not require an assisting tool to complete the suturing procedure. Thus completion of the ultimate goal – developing a tool to successfully suture a wound – could be most simply accomplished with the SILS Stitch. Simplicity in design is a key principle for good design.

The SILS Stitch, is a disposable, manually controlled laparoscopic suturing tool with a gripper style end effector. It is capable of grabbing tissue and passing a needle through it without another assisting tool. It also offers articulation (pitch) of the end effector up to $80^{o}$, and continuous rotation of the wrist joint. With these DOF, plus an additional 6-DOF provided by mounting the automated SILS Stitch on a robotic arm, the proposed design will be able to achieve any orientation in the laparoscopic workspace. The SILS Stitch is able to perform the entire suturing task, all while being controlled with one hand, indicating a simple user interface and elegant internal mechanisms. Some issues identified for automating the SILS Stitch tool include actuation of the pitch joint and accurate position feedback. Actuating the pitch knob will be challenging since it is a stiff joint that requires high torque to actuate. Further, it will be difficult to acquire accurate position feedback about the exact location of the end effector because the end effector is located far from the body of the tool, and it can roll continuously (additionally, the rolling degree of freedom occurs after the pitch degree of freedom).

There are two opposing strategies for solving the problem of automating the SILS Stitch. One consists of attempting to leave the tool intact and interfacing with the existing features. The second strategy aims to open up the tool and interface with the bare mechanisms. Each approach has its advantages and disadvantages. A combination of the two strategies could also be employed. There are several designs that fall under each type of implementation; however the main strategy should be decided first. Below is a decision matrix that compares the different strategies. Note that the score for the designs with respect to some criteria was unknown at this point (i.e. power consumption, damage to surrounding tissue), thus a neutral score of 5 was assigned.

**TABLE 1 - DECISION MATRIX COMPARING SCORE OF EACH DESIGN APPROACH IN EACH CRITERION**

| Criteria | Weight | Raw Score (x/10), 10 is the best | | Weighted Score | |
|---|---|---|---|---|---|
| | | Non-Intrusive | Direct Actuation | Non-Intrusive | Direct Actuation |
| **Weight** | 0.05 | 6 | 9 | 0.3 | 0.45 |
| **Cost** | 0.02 | 5 | 7 | 0.1 | 0.14 |
| **Tool size** | 0.05 | 4 | 9 | 0.2 | 0.45 |
| **Accuracy of end-effector** | 0.1 | 4 | 6 | 0.4 | 0.6 |
| **Ease of automation** | 0.24 | 7 | 4 | 1.68 | 0.96 |
| **Ease of manufacturing** | 0.2 | 8 | 4 | 1.6 | 0.8 |
| **Simple controller API** | 0.05 | 5 | 5 | 0.25 | 0.25 |
| **Maximizing robot workspace** | 0.07 | 5 | 5 | 0.35 | 0.35 |
| **Damage to surroundings** | 0.01 | 5 | 5 | 0.05 | 0.05 |
| **Reliability** | 0.15 | 4 | 9 | 0.6 | 1.35 |
| **Aesthetic appeal** | 0.05 | 5 | 8 | 0.25 | 0.4 |
| **Power consumption** | 0.01 | 5 | 5 | 0.05 | 0.05 |
| **Total** | 1 | - | - | 5.83 | 5.85 |

From above, it can be seen that the completely non-intrusive and the fully intrusive strategies appear to be equally advantageous. The group agreed that the non-intrusive design might be simpler to implement, however the feasibility of reliably actuating the pitch knob without interfacing with the bare mechanism was doubted. The intrusive design would be decidedly more complex, but ultimately more reliable. Since the two strategies are principally different, easily combining the two is not ideal as the individual benefits are lost after the strategies' conglomeration. Thus, the group decided to delay the decision about which approach to employ until further research could be completed. A full design with the intrusive approach was completed, since it was certain that a reliable solution with this approach could be realized. A proof-of-concept was initiated to verify if the pitch knob could be actuated using the non-intrusive approach. The full, non-intrusive design would follow based on the results of the proof-of-concept.

Each of the two designs will be discussed in detail in the following sections.

# 3 DESIGN #1: NON-INTRUSIVE DESIGN

## 3.1 DESIGN

The first design employs a non-intrusive design strategy. The main motivation behind this strategy is the fact that the platform, the SILS Stitch, is a disposable tool. Thus, if design does not modify the integral components of the SILS Stitch, its disposable nature can be upheld and integration of the automation will be simple and easy for those already comfortable and familiar with the SILS Stitch. Else, further modifications will have to be made to sterilize the tool between uses. The goal with this approach is to develop a non-intrusive interface which will mechanically actuate (without any disassembly of) the SILS Stitch. The ultimate ideal is to develop a wrapper that can simply snap on around the existing SILS Stitch, permitting re-use of the automation module but allowing for easy disposal of the SILS Stitch.

Clever mechanical design will be required to elegantly interface with the existing SILS Stitch features in a snap-on wrapper solution. The four modes of actuation required are

- Open/close handles (to open/close the jaws of the end-effector)
- Toggle levers (to pass the needle between the jaws)
- Rotate articulation knob (controls the articulation/pitch of the end effector)
- Rotate end rotation knob (controls rotation/roll of end effector)

Alternative design solutions considered are presented in the following morphological chart (Table 2).

TABLE 2 - MORPHOLOGICAL CHART FOR NON-INSTRUSIVE DESIGN

| Actuation Mode | Ideas | | | |
|---|---|---|---|---|
| **Open/Close Handles (Open/Close Jaws)** | *Magnets* | *Motors and strings* | *Linear Actuator*** | *Mechanical Linkage* |
| | • Attach magnet to each handle<br>• Fulfills binary position requirement<br>• Strong enough force to close handles?<br>• Feedback available? | • Spin a motor and wind up strings attached to the handles<br>• Spin motor in opposite direction to release<br>• Highly reliable? | • Easily procurable<br>• Built-in encoder<br>• Inexpensive<br>• Too large? | • Rigid 4-bar (for example) mechanism with external linear actuator<br>• Repeatable motion<br>• Feedback with high confidence will be easy to acquire |
| **Toggle Levers (switch needle between jaws)** | *Single Linear actuator*** | *Motor and cable* | *Dual Linear Actuators* | |
| | • Push up on one arm; arms are mechanically linked<br>• Add a sensor on the non-controlled arm to provide more reliable sensing (non-collocated control) | • Tie string to each toggle arm<br>• Need small pulleys to route the string to a motor<br>• Sufficient torque?? | • Include one linear actuator for each arm<br>• Gives more motion control (e.g. raise both levels together) | |
| **Rotation Knob (Roll Knob)** | *Sleeve and external gears*** | *Spring-loaded line* | *Worm gear* | |
| | • Design sleeve to fit around the knob<br>• Attach/incorporate gear to the sleeve<br>• Mesh an external gear with the sleeve gear<br>• Actuate external gear with a motor<br>• Able to do this non-destructively?? | • Permanently attach a line to the knob<br>• Stretch string to rotate knob; release to rotate back<br>• Need low spring stiffness<br>• Incorporate strain gauge to measure rotation? | • Design a worm gear mechanism to mesh with the knob grooves<br>• Knob material may have too little friction and insufficient grip in its "teeth" (actually grooves)<br>• Bad for spatial considerations | |
| **Articulation Knob (Pitch Knob)** | *Clamping rollers (1 motor)*** | *Clamping rollers (2 motors)* | *Timing belt* | *Non-contact solution: magnetic?* |
| | • Compressive preload keeps rollers clamped to knob<br>• One motor actuates a gear system which rotates two rollers in same direction on either side of the knob | • Compressive preload keeps rollers clamped to knob<br>• Each roller has its own motor powering it<br>• Motor mismatch may require some slip between roller and knob | • Have timing belt in solid contact with the knob (extra rollers may be required)<br>• Motor coupled to a belt pulley drives the belt and turns the knob | • Similar idea as a DC motor, attach coils or small magnets in each groove of the knob<br>• Install an external magnetic field<br>• Let the Lorentz forces do their work<br>• Will torque be sufficient? |

The best option for each actuation mode has been designated with a "**". The main considerations for selecting the best options include ease of procurement, ease of integration/incorporation into the rest of the design, minimizing the component count, and accordingly, size of the resulting design. A final design has not yet been devised that incorporates each of these components. A rough sketch has been created, and can be seen below. Linear actuators are labeled "S_", since the idea of using a solenoid for linear actuation was being considered at the time the sketch was created. The detailed design and CAD drawings will not be created until a proof-of-concept of the pitch joint is complete.

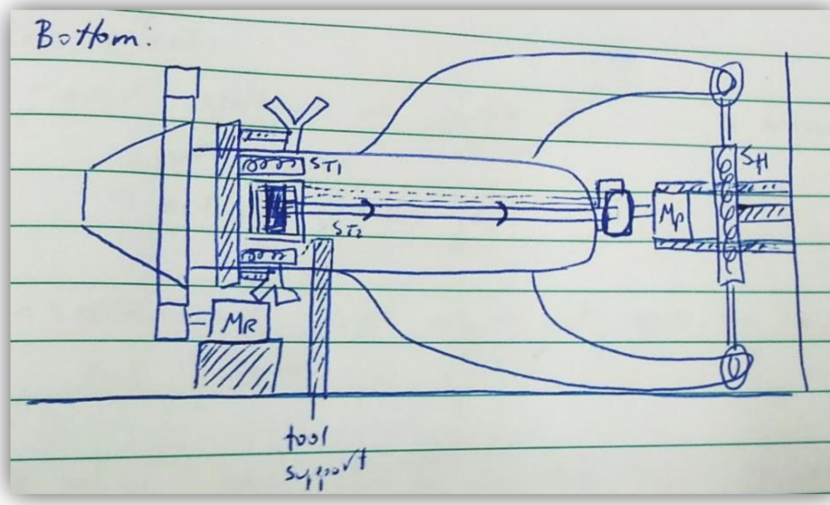



**FIGURE 6 - SKETCH OF NON-INTRUSIVE DESIGN**

## 3.2 Detailed Design

Of the four actuation modes, the pitch articulation has been identified as the most challenging since the pitch knob requires a large amount of torque and it does not offer a large surface area for interfacing. In addition, the available knob surface area has irregular grooves which have been designed for use with a human thumb. The actual amount of torque required to turn the knob has not been measured. A proof-of-concept design is currently under development to validate that an effective, non-intrusive solution for turning the pitch knob could be created. If the actuation of the most difficult degree of freedom is successful, the full detailed design will ensue. If unsuccessful, the non-intrusive approach will be abandoned.

Two strategies for actuating the pitch knob include using rollers, and using a timing belt. In both, slipping on the pitch knob will be an issue, and proper compressive force on the knob will be critical. The first alternative uses the timing belt.

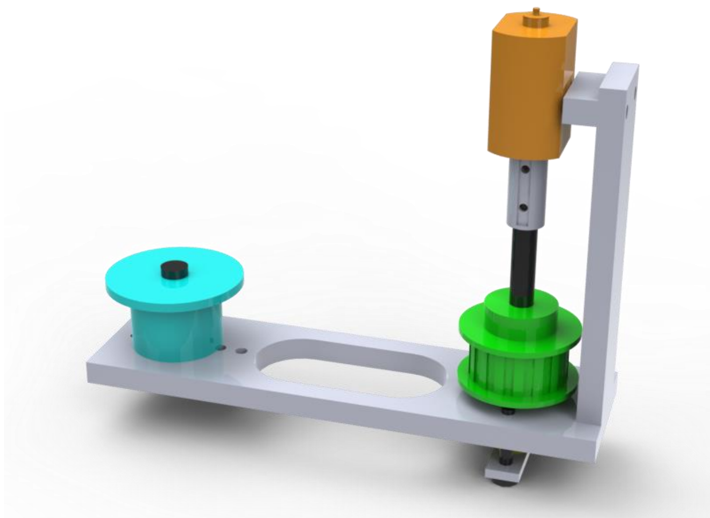


FIGURE 7 - NON-INTRUSIVE APPROACH FOR TURNING THE PITCH KNOB: SINGLE MOTOR AND TIMING BELT PULLEY

As shown in Figure 7, a motor would be coupled to a belt pulley which would drive the belt and turn the knob. The slot will fit in around the tool body. Ensuring solid contact between the belt and the knob will be tricky but vital. The second alternative uses rollers.

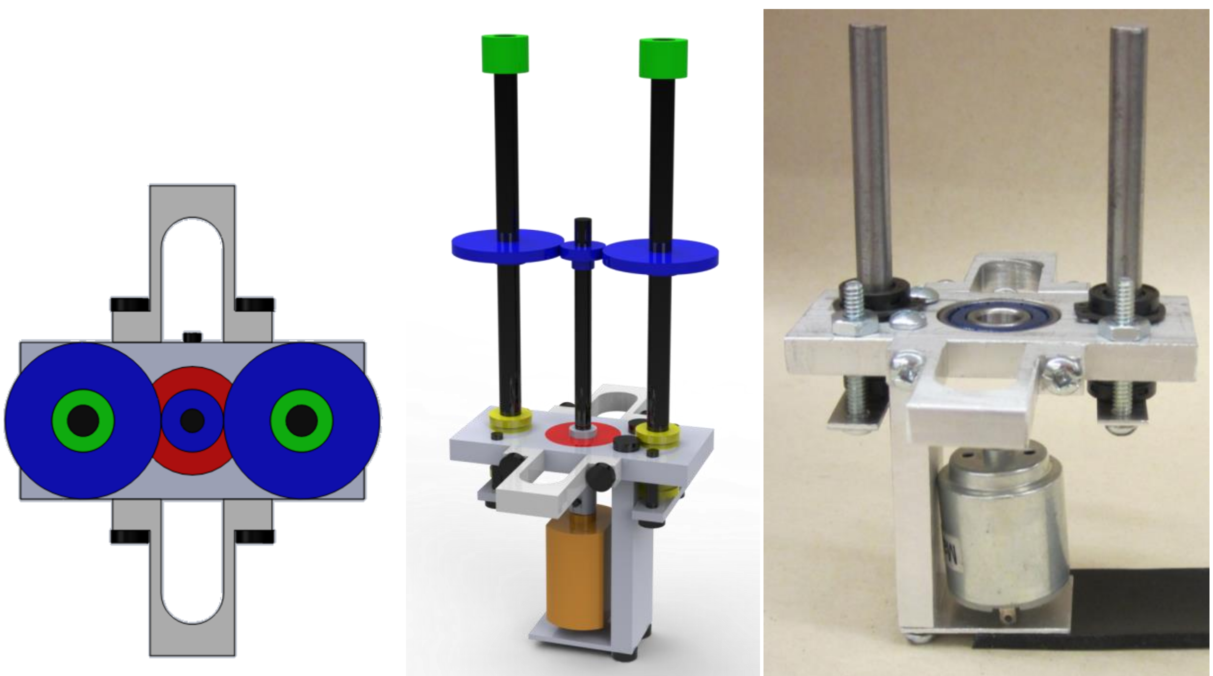


FIGURE 8 - IMAGES OF NON-INTRUSIVE APPROACH FOR TURNING THE PITCH KNOB: USING ROLLERS
(LEFT TO RIGHT: TOP VIEW OF CAD ASSEMBLY, ISOMETRIC RENDERING OF CAD ASSEMBLY, ISOMETRIC VIEW OF CURRENT STATE OF MANUFACTURING)

One motor will actuate a gear system that will turn two rollers (show in green above) in the same direction, and these will be clamped around the knob. Slipping off the knob could be a potential problem, so a support piece may be required high up near the rollers. The rollers currently consist of pieces of neoprene cemented to the shaft. However, research into materials which resemble human skin (with high deformability and yet high friction) is currently underway. The roller solution was deemed to be more feasible thus the first proof-of-concept followed the roller design. While nearing completion, the amount of torque offered by this solution has not yet been tested, but will be done in the near future.

## 3.3 Analysis/Component Selection

The platform for proposed solution is a commercially available manually-controlled tool. As such, the existing mechanisms in the platform have been designed with the proper mechanical advantages such that minimal force is required to actuate the tool. This, combined with the difficulty of measuring forces on actuation points in the tool, has resulted in the initial prototype being initially overdesigned as a proof-of-concept. For the final design, precise measurements on the compressive force required to open/close the jaws, and the torques required to turn the knobs will be taken such that the safety margin is accurately known. Further, due to the small scale of the tool, analysis into the required material was also not necessary. The working forces are so small that any metal (e.g. aluminum), and even plastics (e.g. Teflon), will be sufficiently strong for the housing and external components. Weight should be minimized; however critical components will be manufactured from stronger materials for robustness. The most critical part of the non-intrusive design will be creative solutions for actuating the different modes, as well as an elegant layout of the various actuation points.

As for component selection, some simple calculations were made to determine the length of the timing belt required, and standard sized gears were selected. For electrical components, detailed component selection is discussed in Section 4.3, and for efficient use of resources, the same components selected for the direct actuation design are to be used in the non-intrusive design. The non-intrusive solutions were designed to incorporate the similar components.

## 3.4 Review

The disadvantage of such an implementation is that unless designed very meticulously and carefully, there is a risk of it having an appearance of a haphazardly assembled, “hacked” solution. In addition, some of the components on the SILS Stitch requiring actuation (particularly the pitch knob) may not allow a robust mechanical interface in its existing state.

The advantages, however, are that the solution will be very modular and easy to use – “simply snap it on, connect the electronic interfaces and go”. This will be beneficial for future commercialization of the product. If large numbers of these automated laparoscopic suturing tools will be required to be produced, modifying every SILS Stitch may be unfeasible, and a wrapper solution would be the best avenue. However, considering the defined scope of this project, the future commercialization is not a priority since this is far in the future of the needed solution. The solution to be designed for CIGITI must first and foremost satisfy all the specified constraints, namely reliability.

The result of the proof-of-concept study on the actuation of the pitch knob will determine whether or not the remainder of the non-intrusive design will even be attempted. Results regarding the torque offered by this design are expected to be produced in the coming weeks, and the design will be finished before the New Year.

## 3.5 Summary

This design is still in the proof-of-concept stage of development. The critical roadblock towards determining the feasibility of the non-intrusive design is actuation of the pitch knob. Requiring high torque and offering a small surface area for interfacing, it will be difficult to interface reliably with the pitch knob. Designs have been suggested for the other actuation modes. Accurate feedback remains to be incorporated in the design. If an effective proof-of-concept design is developed for the pitch knob, the rest of the design will be non-intrusive since this strategy requires lower levels of complexity. If designed well, an elegant wrapper solution could be devised to simply snap on to the SILS Stitch tool and interface with its existing features.

# 4 DESIGN #2: DIRECT ACTUATION DESIGN

## 4.1 DESIGN

The second design concept solves the issue of interfacing with the SILS Stitch tool by completely removing the casing of the original tool and interfacing with the bare wires and control rods. It is believed that this solution will provide a more reliable control system since actuation points will be solidly connected, however by taking the tool apart, many more unexpected issues are possible. With the casing removed, each of the four actuation points (roll, grip, toggle and pitch) are exposed. The base of the design is a rectangular block that fixes the tool in a precision coupling to assure that the tool is securely attached to the base. All actuation points are mounted on this base block.

While developing the Direct Actuation Design, the approach used was to analyze the internal mechanisms of each individual DOF and design a method of actuating each. The final assembly of the design is shown in Figure 9.

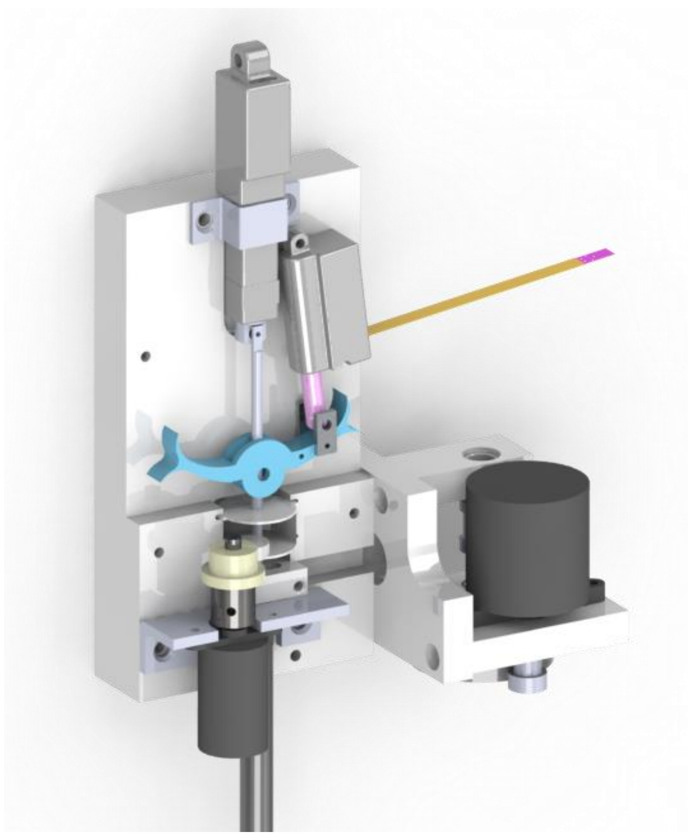


**FIGURE 9 - DIRECT ACTUATION DESIGN ASSEMBLY, SHOWING ALL FOUR ACTUATION MODULES**

The grip DOF was the first focus of the design. Considered solutions included the use of a linear actuator, or a motor and lead screw assembly. It was ultimately determined that a high power linear actuator directly coupled to the grip push/pull rod would actuate the grip satisfactorily for this proof-of-concept design phase. In the next design iteration, a smaller linear actuator with a lever arm mechanism to provide mechanical advantage on the push/pull shaft will be employed to minimize space occupied.

The toggle DOF that controls which gripper jaw holds the needle and was next analyzed. Again, linear actuators and lead screw assemblies were considered. The most important feature was the mechanism which would interface with the push/pull rods. The placement of the push/pull rods must be very precise to accurately grip the needle in the tool's jaw. Therefore, the decision was made to keep the toggle mechanism originally used in the SILS Stitch tool, which helps guide the push/pull rods to grip the needle properly. The toggle mechanism is coloured pale blue in Figure 9.

Actuating the roll DOF was fairly straightforward. The roll shaft rotates continuously and can be driven with a rotational motor and a spur gear. The roll DOF is subject to significant backlash, however, and the explored solutions to actuate this DOF focused mainly on overcoming this backlash. Machining new gears for the already present SILS Stitch gearbox was considered, as well as building a new gearbox altogether. Finally it was determined that if a rotational encoder could be placed on the roll shaft, decoupled from the drive motor, the position of the roll shaft could be accurately determined regardless of the backlash present in the drive mechanism. This eliminated the need to machine new gears.

The pitch DOF was identified early in the project as the most challenging to actuate as it is very stiff. Therefore the actuator driving this DOF needs to be very powerful. The pitch is actuated using two cables in a pull/pull configuration. Linear actuators were considered to actuate each individual cable, as well as a spool which would wind each cable. The spool technique was chosen, as it would allow for simpler control of the pitch and allow a constant tension to be maintained on the joint.

The alternative design solutions considered are presented in the following morphological chart (Table 3).

**TABLE 3 - MORPHOLOGICAL CHART FOR DIRECT ACTUATION DESIGN**

| Degree of Freedom | Ideas | | |
|---|---|---|---|
| **Grip** | *Actuation Mechanism* | *Mechanical Advantage* | *Damage control to tool* |
| | • Linear actuator directly coupled to actuation shaft<br>• Motor and lead screw assembly | • Use lever arm to provide additional mechanical advantage to drive actuator<br>• 1:1 direct drive | • Current limiting on actuator<br>• Physical stops |
| **Toggle (Needle Passing)** | *Actuation Mechanism* | *Push/Pull Rod actuation* | *Damage control to Tool* |
| | • Linear actuator<br>• Motor and lead screw assembly<br>• Rotational motor coupling | • Keep pre-existing toggle mechanism (blue piece in Figure 9)<br>• Drive each rod independently | • Current limiting<br>• Physical Stops |
| **Roll** | *Actuation* | *Backlash Control* | *Worm gear* |
| | • Mesh actuation gear with pre-existing gearbox<br>• Attach a new gear directly to the roll shaft. | • Spring load shaft.<br>• Machine new gears for gear box<br>• Install non-collocated rotational sensor on shaft for precision control | • Conserve space by using worm gear to interface with shaft gear |
| **Pitch** | *Actuation Mechanism* | *Mechanical Advantage* | *Timing belt* |
| | • Rotational motor driving spool to wind pull/pull cables<br>• Linear actuators to drive cables | • Additional gearing after motor's gearbox<br>• Lever mechanism for linear actuators | • Strain gauge sensor at pitch joint to monitor degree of bend. |

## 4.2 DETAILED DESIGN

All electrical systems are designed for simplicity. Stepper motors are used where precision was necessary and subsequently geared to achieve the proper step resolution. These stepper motors are driven by a simple 12V stepper motor driver, capable of current limiting to avoid damaging the tool. The selected linear actuators are DC continuous motors with potentiometer feedback to achieve accurate positioning. These actuators are driven by DC motor drivers, again with current-limiting ability to mitigate damage to the tool.

The roll degree of freedom (DOF) is the simplest to actuate. The roll DOF is actuated by rotating a central shaft about its long axis. As the control rod spins clockwise or counter clockwise, the "wrist" of the end effector turns at the same rate. The control rod is actuated using a coaxial gear box. While the gearbox reduces the torque required to actuate the roll DOF, it also introduces significant backlash as the interface between the control rod and the gearbox is very loose. Since this interface is so deeply embedded in the platform tool, it will not be possible to eliminate and as such will have to be compensated for in the controller design.

The same axial control rod also actuates the end effector's "grippers" using a push-pull interface. As the rod is pulled away from the end effector, the grippers close. Likewise, the grippers open as the rod is pushed towards the end effector. Due to the four-bar linkage being used to actuate the grippers in the end effector, this is a linear relationship. While mechanically simple to actuate, the control rod requires significant torque to pull which complicates the actuator selection since it is difficult to increase linear mechanical advantage.

Passing the needle between the gripper jaws is toggled by two independent control rods running down the tool shaft. The rods alternate positions, with one always full-forward and one full-back. It is believed that the tolerance on the positioning of these rods is very precise (in order to successfully pass the needle back and forth), and as such it can be seen great care had to be taken to design and assemble the mechanism. As such, the original toggle (previously hand operated) will be used in order to maintain all spacing and actuation trajectories. This toggle has been modified to simplify mechanical actuation and fit within the new control base.

Finally, the pitch mechanism is the most complicated degree of freedom to actuate. The flexible nature of the two wires used to actuate the pitch, combined with the high torque requirement to actuate the end effector creates significant design challenges to overcome. Wire routing is necessary due to space limitations close to the body of the tool. As a result, a purpose-built housing was 3D printed in order to allow the wires to be routed $90^{o}$ to the actuator. This housing is expected to induce significant friction, which will be explained further in this report.

## 4.3 ANALYSIS/COMPONENT SELECTION

Of the four degrees of freedom (DOFs) that were in need of actuation drivers, two were identified as smooth and simple to actuate, and two were identified as stiff to actuate. It was known that the stiff DOFs would need high torque drivers to actuate them. The smooth DOF were roll and toggle. And the stiff DOF were pitch and grip.

A series of linear actuators and stepper motors were identified early as applicable for this project, based on group members' experience with the components. The linear actuators were selected from the Firgelli P12 and L12 series and the stepper motors were the Minebea PGXXS series.

The Minebea geared stepper motors have a very small step angle ($0.1^{o}$ – $0.5^{o}$). They also have plastic gear boxes which makes them much lighter than comparable motors with metal gearboxes. Finally, they have high output torque for their size. All these characteristics come together to make this series of geared stepper motors the best choice for this project, with very high precision and output torque for their small form factor, weight and cost. A typical motor from this series is shown in Figure 10.

**FIGURE 10 - A MINEBEA STEPPER MOTOR WITH LIGHT WEIGHT PLASTIC GEARBOX (SOURCE: DIGIKEY)**

The Firgelli PQ12 and L12 series of linear actuators was chosen for similar reasons to the stepper motors. They are light and have a small form factor. A potentiometer is built in to the linear drive systems, providing 0.25 [mm] accuracy on the extension of the arm. Coupling the drive encoder with the linear actuator allows additional space and design effort to be saved. Figure 11 shows the Firgelli L12 linear actuator used in this project. The PQ12 actuator is a smaller but less powerful version of the L12, used for the needle toggle assembly.

**FIGURE 11 - FIRGELLI L12 SERIES LINEAR ACTUATOR WITH 0.25[MM] RESOLUTION. (SOURCE: ROBOTSHOP)**

Based on the classification of the DOF as stiff or smooth, the highest power and lowest power output components of each series were chosen respectively. The torque requirements of the motors were compared to measured values of torque for the roll, grip and toggle DOFs, however the pitch DOF could not be measured because the friction caused by routing the wire through the conduit which would be present in the final design could not be estimated. Therefore for the pitch, the highest torque stepper motor within the weight and financial budgets was chosen.

The weight budget of 2.5 [kg] is a strict constraint because it is the maximum load the DENSO arm can lift. The highest weight component of the design was identified to be the structure of the tool wrapper. A light, rigid plastic had to be found to meet this constraint. A mix of high density plastics were used to build the structure of the tool. It was quickly realized that PVC, although very strong, was too heavy for this application.

The electrical components were sourced based on the actuators chosen. The linear actuators required a simple H-bridge driver, and the stepper motors required a bipolar stepper driver. An Arduino Uno microcontroller was chosen to control the robot, and so all motor driver chips need to be compatible with the 5V logic of the Arduino Uno board.

The A4983 stepper driver chip was chosen to drive the stepper motors. This chip provides the necessary current throughput, simple two bit step and direction control and current limiting capabilities.

The MC33887 H-bridge chip was chosen to drive the linear actuators. This chip provides the necessary current throughput to drive the linear actuators. A current limiting circuit will be considered to ensure that the linear actuators do not pull too hard on the tool and damage any of the internal components of the tool.

## 4.4 Review

While the assembly has been designed to be as reliable yet simple to build as possible, there are still issues expected to arise during the prototyping stage of this project. Even though these issues are anticipated, due to their nature they cannot be addressed until the extent of each can be evaluated after assembly.

The routing block is one significant potential issue. Since tensioned cables will be making a $90^{o}$ corner, significant friction along the path could be induced. The severity of this friction will depend not only on the tension of the control cables, but also the material from which the block is constructed. Currently it is planned to print the routing block using a 3D printer. While 3D printing offers a simple way to create the complex geometry required by this part, the layered construction of printing is likely to cause significant friction as the braided cables rub along each of the edges. Different lubricants will be tested to attempt to mitigate this issue. If lubricant is insufficient, the part could be machined to create a smoother channel through the routing block. While smoother, this alternative would be significantly more difficult to build.

Passing the needle between grippers is actuated by moving a toggle arm back and forth along an arc. While designed to interface with a human hand, the current design actuates this using a DC linear actuator. Since the OEM toggle is being used, the trajectory of the movement should not pose a problem. The X-Y positioning of the toggle however is critical. Since this design incorporates a completely redesigned case, the toggle position had to be measured carefully and reproduced in the new case. If the position of the toggle is incorrect, the control arms which actuate the needle-passing mechanism will not achieve a full range of motion and the mechanism will most likely not work. Again this issue cannot be resolved until the extent of the problem can be assessed after assembly.

Since the design incorporates a precision surgical tool, great care must be taken to assure the tool is not damaged by the added actuators. The new actuators can put significant stress on different parts of the tool and in many cases are interfacing with the tool in a manner completely different from the original designers' intent. Techniques such as actuator current-limiting will be used extensively to minimize the chance of damage to the tool. Even so, damage is likely during the prototyping stage as the needle-passing mechanism has already been damaged on one of the tools during disassembly for design.

Finally, the tool was designed to load the needle into its grippers in a very specific way. A special tray is used to hold the needle in the correct orientation while the gripper is positioned over the needle. Finally, the entire needle toggle is pushed forwards (rather than pivoting about the center of the toggle), at which point the tool grasps the needle. This motion is very hard to replicate mechanically and investigation will have to be performed with the new prototype to determine how this can be replicated. It is possible that the whole toggle interface of this design will have to be overhauled if loading of the needle is not possible.

## 4.5 Summary

The final design of the first prototype of the tool described in this section is currently under construction. As of this writing, it is approximately 80% complete.

Once the prototype is assembled, it is expected to reinforce and disprove certain design challenges that were identified as problems during this phase of design. The highest priority among those design concepts that need validation are the pitch module and the needle toggle module.

The main validation for the pitch will be whether the double wrapped spool mechanism is easy to assemble and whether it maintains a constant tension on the pitch actuation cables. Another point of validation will be to determine whether the motor is strong enough to actuate the pitch.

The needle toggle must position the actuation forks very precisely to grip the needle correctly. It will be obvious whether this actuation point functions well if the tool can pass and hold the needle firmly without dropping it.

The prototype will be tested thoroughly and care will be taken to observe these two actuation points in particular. A test plan will be developed which will outline each of the expected functions of the tool, and then validate the success of each of these. For example, functions such as "roll end effector," "pass needle," etc. will be included in the test plan and will be formally verified. As some issues in the actuation of these degrees of freedom are expected, changes will be made to the next design revision based on the behaviour observed in the actuation of this design.

# 5 Future Improvements

Several design solutions have been considered for each mode of actuation. These are mainly concerned with mechanical design. The next steps considered incorporate feedback into the design. Feedback on the following parameters will be desired for a complete, "smart tool" design:

- *Position of handles* – fully open, fully closed, intermediate state. Note, the needle cannot be passed between the jaws unless the jaws are fully closed. Also note, turning the pitch or roll knobs requires more torque when the jaws are closed (due to internal mechanisms of the SILS Stitch).
- *Position of articulation (pitch) of end-effector* – shall it be measured at the knob, or at the tip? If at the tip, the issue of the tip being able to rotate continuously and being located far from the actuators must be addressed.
- *Position of rotation (roll) of end-effector* – shall it be measured at the knob, or at the tip? Same issue as pitch. Note that significant backlash is inherent in the SILS Stitch design.
- *Position sensor on toggle levers* – determine if left side of lever is raised, right side of lever is raised, or is in intermediate state (i.e., does the left jaw hold the needle, the right jaw, or is it currently being passed).
- *Verification of needle presence* – an additional sensor verifying the position of the needle (left jaw, right jaw, being passed, dropped); would also serve to detect if the needle has been loaded successfully.

The most prominent issue for feedback is that the end-effector can roll continuously and is located far from the actuators. Having wires run along the shaft is not an option due to the nature of use of the tool and the environments in which it must operate. Further, routing the wires properly while allowing the end effector to roll continuously will be challenging. Limiting the roll range is a possibility, but ideally the capabilities of the platform will not have to be suppressed by the automated design. Research is therefore currently being done into wireless technologies, including potential solutions such as RFID, to offer feedback. Supplying power is still an issue – the end-effector must be as small as possible since it must not only fit through a trocar but induce the least amount of damage to surrounding tissue during the operation. A battery on the end-effector would therefore not be feasible.

# 6 Schedule and Budget

## 6.1 Schedule For Manufacturing

Manufacturing schedules dictated how the project timeline was initially set up. Time was budgeted for two prototypes and one final construction. The first prototype would be built by early December 2012, and the second one by late January 2013. The group then did a more specific time budget/schedule for the first half of the available timeline from September to December 2012 (i.e. the Fall term). This would allow the group a chance to reflect on its performance in the first half of the design process, and reconsider the time allocation for difficult aspects of the project once half the project was complete. The Gantt chart in Appendix A shows the predicted time to be spent on each aspect of the project in red and the actual time spent in blue. The project has fallen slightly behind schedule in the past few weeks, however the group is confident they can recover and complete the project comfortably within the allocated time.

## 6.2 Budget Expected Chart

The following is an estimated budget for the expected expenses necessary for successful completion of the project. A complete version of the budget is found in Appendix B. Below is a summary of the expenses, broken down into the major divisions of expenditures. It can be seen that the project is well within its allocated $2600, signifying the group is staying within budget. Further, the majority of these purchases entail components which will be reused for future prototypes and the final design. Thus, the group confidently predicts staying within the budget for the remainder of the project.

**Table 4 - Summary of Expenditures**

| Item | Total Cost |
|---|---|
| Mechanical Subtotal | $132.00 |
| Electronics Subtotal | $505.00 |
| Sensor Subtotal | $230.00 |
| Material Subtotal | $100.00 |
| Tool Subtotal | $0.00 |
| Subtotal | $967.00 |
| Taxes and Shipping | $125.71 |
| TOTAL | $1092.71 |

# 7 Conclusions and Recommendations

In conclusion, the project is progressing at a good rate and is on schedule to be completed in the Winter academic term in accordance with the course schedule. While there are currently two different potential mechanical designs, this is not anticipated to cause project delays since prototyping of both designs is almost complete. With completed prototypes, the group will be able to validate each design and determine the true advantages and disadvantages of each solution. With this new information, a final design can be selected over the Christmas academic break, and the project will move forward in the Winter term with a single design.

Despite having two different potential designs, many elements remain the same since a common tool is being used and many of the electronics supporting the mechanical designs are identical. Both designs use an Arduino microcontroller to coordinate the tool's movements and make use of the same lines of stepper motors and linear actuators. These commonalities have allowed the group to order all necessary electrical (and electromechanical) parts for the system in advance of the Winter term. This will greatly expedite the final prototyping process in the Winter since lead times will no longer be on the critical path.

Initial cost estimates are significantly below the cost constraint imposed upon the group. With less than 40% of the budget spent as of the time of writing and two prototypes nearing competition, budgetary constraints are not anticipated to be an issue during final prototyping stages. These cost savings are largely due to the "hobbyist" class of actuators and controllers being used for this project. Since the tool's primary purpose is a proof-of-concept for the partner research group, this class of actuators is sufficiently accurate and allows for design revisions without prohibitive costs.

It is recommended that over next month the team consolidate the two design concepts into a single, final design. This is necessary to refocus the team efforts on a single project and as a result make better use of the limited time remaining in this project. This can only happen once both prototypes can be evaluated and each of their identified potential issues can be compared numerically.

With the identified issues quantified, solutions to these issues need to be found in order to achieve the high precision and reliability required by the project constraints. It is recommended that a second prototype should be constructed early January which implements the proposed solutions to solve some of the identified issues. A final prototype should then be constructed late February in order to allow time for final testing and minor modifications.

Finally, it is recommended that the group schedule mandatory hours during the Winter academic term where their time must be spent on project related tasks. While some of these time slots may be used for formal meetings, they are being allocated with the intent of assuring that a constant and significant amount of time is being spent on the project despite heavy course loads. These times will be scheduled at the beginning of the term at times that are least inconvenient to all group members. This recommendation is not a response to particular group members not contributing an equal amount, but rather a realization by the group as a whole that more time must be spent on this project to achieve the stated goals and constraints. In reflection, the group discovered that this project was often pushed down in priority next to other courses' assignments and projects, mainly due to the psychological effects caused by the more imminent deadlines for the other courses. Breaking the project down into smaller tasks with short deadlines may dissolve the illusion and improve motivation since more minor, manageable tasks are easier to take on and complete than a large, intimidating project.

# 8 TEAMWORK EFFORT

All group members have contributed significant and meaningful effort to the project. The teamwork was efficient in carrying out the project, as it centered on good communication, cooperation and coordination. The group worked closely through the needs assessment and high level design stages of the project to develop a well constrained problem. With the problem defined, it became apparent that two distinct and different design approaches needed to be pursued. As a result the group split off into two sub-groups, each focused on one of the two design approaches. While there have been two concurrent designs progressing throughout the second half of this term, the group has maintained a united focus and has kept everyone updated at regular intervals. To ensure coordination between the members, frequent short meetings are held where the group discusses its current state of progress, the group's goals for the near future (i.e. the next day or the next week), the high-level task each member plans to complete (checklists are often created for this purpose), as well any other issues which may be prevalent at the time. The interpersonal relationships between the three group members are very positive, thus open communication is encouraged and always achieved.

## 8.1 KARL PRICE

Karl Price was the group member who originally developed the idea for the project. Having worked with CIGITI for three work terms, Karl was very familiar with the Centre and its current project. He realized that developing a suturing tool for the *KidsArm* would be a good fourth year design project and subsequently brought it forward. Now that this project has been chosen, Karl continues to act as the liaison between the group and CIGITI. With multiple group members, having a single point of contact ensures that communications with CIGITI are streamlined and efficient. Karl has also undertaken managing project scheduling for the group, assuring not only that meetings are scheduled well in advance but also tracking the progress of different project tasks.

Karl, along with Brock, worked on designing the Direct Actuation Design. Karl's main focus was designing both the pitch actuation module as well as the toggle module. The pitch actuation module was a significant design challenge since a method had to be devised to actuate two control cables in a very precise manner such that the tool's pitch assembly moves in a controlled manner. Karl also led the design for the toggle module which actuates the tool's needle passing functionality. Finally, during the prototype manufacturing stage, Karl has been responsible for manufacturing the parts he designed. Manufacturing was split in this way since each designer would be most familiar with their respective parts and thus more capable of making quick modifications should there be assembly issues.

## 8.2 ANGELICA RUSZKOWSKI

Angelica Ruszkowski has been tasked with managing the project budget. She spearheaded the project's initial budget and has been keeping track of group spending as the prototypes are assembled. While the exact amount spent on this project is not a significant concern since CIGITI and the University of Waterloo will be reimbursing some expenses, detailed records have to be maintained to assure that the reimbursement requirements of both organizations are satisfied at the end of the project.

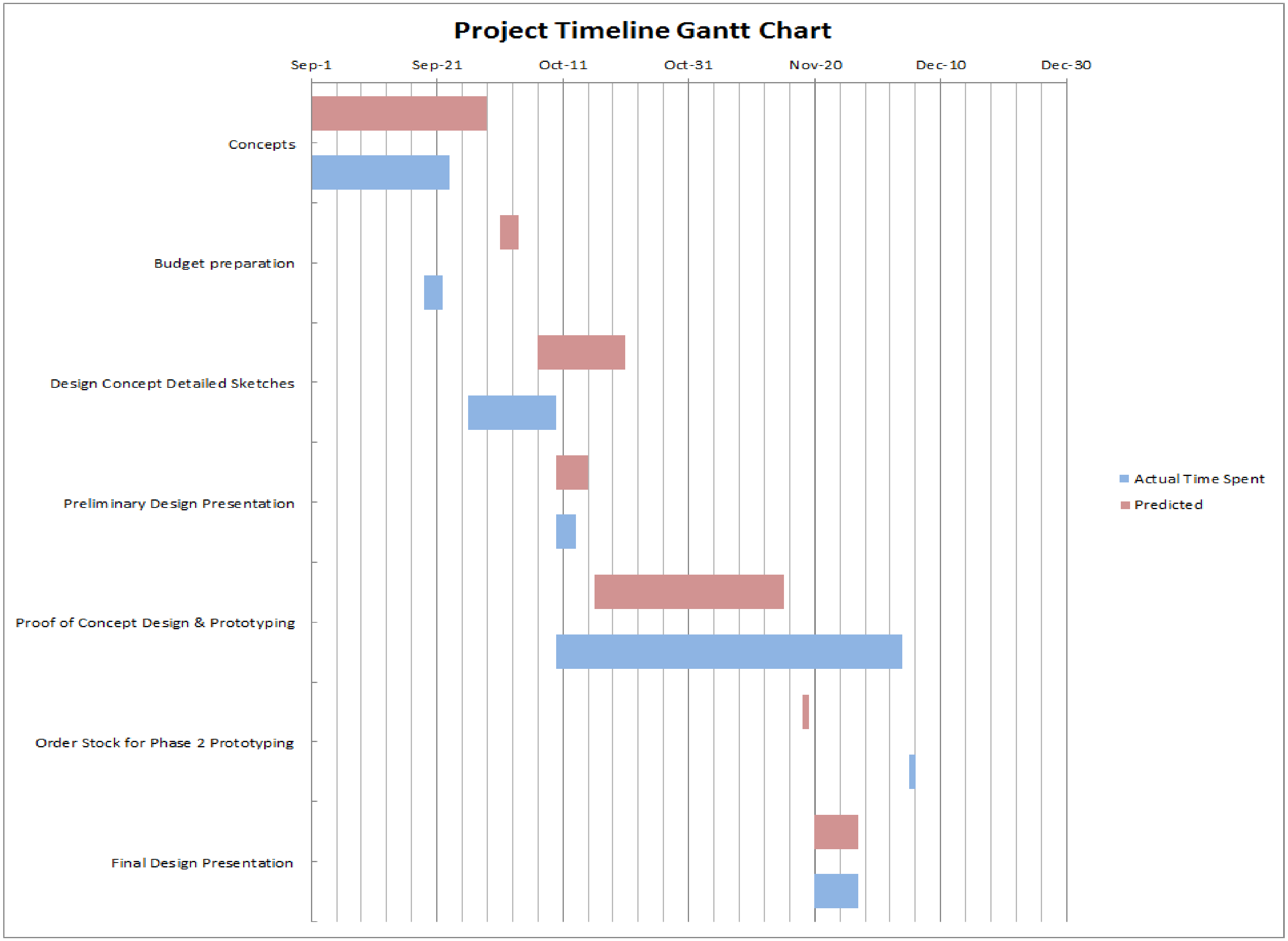
Angelica worked primarily on the Non-Intrusive Design, developing a high level design for each of the tool's different degrees of freedom which would allow actuation without removing the tool's handle enclosure. While all high level designs were produced, it was quickly realized that the pitch actuation would pose the most significant challenge for this design strategy. As a result, it was decided as a group that detailed designs would be made and subsequently prototyped for the pitch joint actuation before proceeding further with this design. If the pitch could not be actuated successfully, the tool would have to be taken apart thus negating the advantages of this design strategy. Due to time constraints, Angelica has also contributed towards manufacturing occasional components for the Direct Actuation Design as well.

## 8.3 Brock D. Kopp

Brock Kopp has been in charge of procurement for the project. Working with each member to collect and combine orders, Brock has been responsible for keeping track of all incoming shipments and their timelines. By minimizing the number of orders being placed, the group has been able to make significant savings in shipping costs. Brock has also brought significant product design and machining experience to the group, having spent multiple work terms in a prototyping facility performing mechanical design and production.

Brock's major design contributions have been working with Karl to develop the Direct Actuation Design. Brock built the housing for this design. The housing had to be capable of securely attaching the SILS Stitch to the robotic arm while encasing all joint actuation modules. Brock also designed the cable routing block which reroutes the pitch control cables away from the tool's axis towards the pitch actuation module. This block, ultimately 3D printed, needed to reroute the control cables without affecting the actuation of the tool's other three control arms exiting the tool shaft. Brock also designed the mount for the roll actuator motor which allowed the motor to align with the tool's existing gearbox. Finally, Brock designed the grip actuation module including selecting the linear actuator and assuring proper alignment of the shaft and actuator.

# APPENDIX A – GANTT CHART



## APPENDIX B - BUDGET

| Item | Qty | Cost/Unit | Total Cost | Details |
|---|---|---|---|---|
| ***Mechanical*** | | | | |
| Gears | 4 | $10.00 | $40.00 | • For mechanical connection between motor and mechanism |
| Bearings | 3 | $10.00 | $30.00 | • For coupling between various components (namely shaft and stationary housing) |
| Timing Belt | 2 | $2.50 | $5.00 | • For proof-of-concept design for non-intrusive actuation of pitch knob |
| Belt Pulley | 1 | $7.00 | $7.00 | • For proof-of-concept design for non-intrusive actuation of pitch knob |
| Miscellaneous Mechanical Components | 1 | $50.00 | $50.00 | • Screws, nuts, bolts |
| *Mechanical Subtotal* | - | - | $132.00 | - |
| ***Electronics*** | | | | |
| Arduino Board | 1 | $30.00 | $30.00 | • Arduino Uno |
| Linear Actuator | 1 | $80.00 | $80.00 | • One for actuation of handles/jaws<br>• One for actuation of toggle levers |
| Stepper Motor – small | 2 | $40.00 | $80.00 | • For actuating roll of end-effector |
| Servo Motor – large (high torque) | 2 | $40.00 | $80.00 | • For actuating pitch of end-effector<br>• Also used in non-intrusive proof-of-concept of actuating pitch-knob |
| Breadboard | 1 | $10.00 | $10.00 | • For developing electric circuits |
| Motor Drivers | 6 | $15.00 | $90.00 | |
| Miscellaneous Components | 1 | $100.00 | $100.00 | • Resistors, capacitors, headers, jumpers, lead wire, voltage regulators etc. |
| Power Supply | 1 | $35.00 | $35.00 | |
| *Electronic Subtotal* | - | - | $505.00 | - |
| ***Sensors*** | | | | |
| Flex Gauge | 1 | $30.00 | $30.00 | • Feedback on articulation |
| Rotational Encoder | 1 | $60.00 | $60.00 | • Feedback on rotation of end-effector |
| Linear Encoder | 2 | $65.00 | $130.00 | • Feedback on toggle switch position<br>• Feedback on handle position (open/closed); corresponds to jaw position |
| Optical Sensor | 1 | $10.00 | $10.00 | • Validation of needle position/presence (checks if needle dropped) |
| *Sensor Subtotal* | - | - | $230.00 | - |
| ***Materials*** | | | | |
| Plastics | - | $20.00 | $20.00 | • For housing components |
| Aluminum plates | - | $20.00 | $20.00 | • Small pieces may be acquired from machine shop without charge |
| Precision ground shafts | 5 | $12.00 | $60.00 | • For proof-of-concept design for non-intrusive actuation of pitch knob |
| *Material Subtotal* | - | - | $100.00 | - |
| ***Tool*** | | | | |
| SILS™ Stitch Tool | 1 | $600.00 | $0.00 | • Base platform for prototype designs<br>• Donated by CIGITI (research partner) |
| *Tool Subtotal* | - | - | $0.00 | - |
| Subtotal | - | - | $967.00 | - |
| Taxes and Shipping | - | - | $125.71 | - |
| TOTAL | - | - | $1092.71 | - |

## APPENDIX C - TECHNICAL DRAWINGS

The following pages of this appendix include the technical drawings for all three prototype designs. The first two designs presented are the non-intrusive pitch actuation designs. Last, the Direct Actuation Design is presented.