EndoVision:
A prototype robotic laparoscope and
telementoring system allowing intuitive
endoscopic visualization

by

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B.Sc. (Mechanical Engineering), University of British Columbia, 2015

Project Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Engineering

in the
School of Engineering Science
Faculty of Applied Sciences

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SIMON FRASER UNIVERSITY
FALL 2018

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# Approval

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**Degree:** Master of Engineering in Biomedical Engineering  
**Title:** EndoVision: A prototype robotic laparoscope and telementoring system allowing intuitive endoscopic visualization

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**Date Defended/Approved:** December 14, 2018
Abstract

This project is for the development of a prototype system for endoscopic visualization for minimally invasive surgeries (MIS). The system will assist a surgeon in adjusting and maintaining the field of view (FOV) of an endoscopic system through head motions alone, relieving the need for hands-on adjustment of a camera scope. A surgeon would wear a head-mounted display (HMD) to visualize the area of interest. A market-ready device would include real-time web communication allowing remote surgeons to provide audio and visual feedback during a surgery.

This medical device would reduce the number of medical staff needed for an MIS procedure, as well as providing surgeons with assistance from other medical professionals over the web, increasing the success rate of MIS procedures.

Uses for this device include: Providing intuitive control of the surgical FOV, training of surgeons in MIS, and as a platform for real-time communication between surgeons at a distance.
# Table of Contents

- Approval ........................................................................................................... ii  
- Abstract ............................................................................................................... iii  
- Table of Contents ................................................................................................ iv  
- 1. BACKGROUND & MOTIVATION ..................................................................... 1  
- 2. PROJECT SUMMARY ..................................................................................... 3  
- 3. PROJECT DETAILS .......................................................................................... 3  
  - Scope ................................................................................................................... 3  
  - Materials ........................................................................................................... 4  
  - Stakeholders ...................................................................................................... 4  
  - Project Timeline ................................................................................................ 4  
  - Project Budget .................................................................................................. 5  
- 4. PROJECT CHAPTERS ....................................................................................... 5  
  - Chapter 1 – Sept 16, 2018 .............................................................................. 5  
  - Chapter 2 – Oct 1, 2018 ................................................................................... 9  
  - Chapter 3 – Oct 15, 2018 ................................................................................. 12  
  - Chapter 4 – Oct 29, 2018 ............................................................................... 21  
  - Chapter 5 – Nov 11, 2018 .............................................................................. 25  
  - Chapter 6 – Nov 26, 2018 .............................................................................. 32  
  - Chapter 7 – Dec 03, 2018 ............................................................................... 39  
- 5. DISCUSSION ................................................................................................... 40  
- 6. RISK MITIGATION .......................................................................................... 41  
- 7. PROJECT CONTINUATION .......................................................................... 41  
- 8. CONCLUSION .................................................................................................. 42  
- 9. REFERENCES .................................................................................................. 43
1. BACKGROUND & MOTIVATION

As the population in North America continues to age, more strain is being put on an already overburdened healthcare system, and any technologies or techniques which increase speed, success rates, and reduce patient recovery times will be highly valuable in the coming years. Minimally Invasive Surgery (MIS) is one of these techniques.

Laparoscopic, or “keyhole” surgery, is a rapidly emerging type of MIS in which the surgery is performed through small incisions around the point of interest. Surgeons use a series of long, slender tools, including a camera scope, to reach through the opening and perform the operation inside the patient. Over 960 thousand cholecystectomies (gall bladder removals) are performed laparoscopically each year in the U.S. alone, and procedures such as hernia repairs, gastric bypass, bowel resection, and organ removal are now routinely carried out laparoscopically2,3.

Due to their success rate, laparoscopic surgeries are becoming more and more common; however, the procedure inherently involves more intricate optical and mechanical tools, which cause difficulty for the surgeon and limit laparoscopic surgical applications. Visualizing the surgical area is one of the challenges in a laparoscopic procedure, and this project aims to make this more intuitive for all surgeons.

Another emerging concept in surgery is telemedicine. Telemedicine is the use of information technology to provide medical care from a distance. It is estimated that more than 2 billion people worldwide have
no access to basic surgical care\(^7\). With improvements in infrastructure such as high speed internet, professional health care may be provided to remote and developing areas via telemedicine.

Telementoring is a subset of telemedicine, and allows specialists to train and assist fellow medical professionals over long distances. This can improve patient outcomes in rural communities while avoiding costly transfers and making efficient use of a surgeon’s time\(^8\).

Widespread use of telementoring services is yet to be adopted, however some surgeons will resort to using Skype or other video calling platforms to seek assistance or get second opinions during surgeries.

In the current medical device market, several products exist which aim to improve the optical or mechanical aspects of the laparoscopic procedure:

The Da Vinci surgical system is the only surgical robot of its kind and is able to perform many types of minimally invasive procedures. However, at a cost of close to US$2 million, it is not an affordable option for remote or developing regions\(^4\).

![Figure 2: Da Vinci robotic surgery setup.](image)

Advanced laparoscopes made by Stryker and Olympus attempt to improve optical field of view and add depth perception. While typical laparoscopes are rigid and must be pivoted through the incision, the EndoEye Flex and Ideal Eyes articulating laparoscopes bend up to 90 degrees in every direction using levers on the handle\(^5,6\).
2. PROJECT SUMMARY
The full robotic laparoscope complete with telementoring features would include the following: A robotic articulating laparoscope with a stereoscopic camera system, a headset with built-in accelerometers allowing the scope to move relative to head orientation, as well as an online telementoring system which allows a remote surgeon to watch live video of the surgery and provide real-time audio and visual feedback to the operating surgeon.

3. PROJECT DETAILS

Scope
Due to time and budget limitations, the scope of this project has been limited to a portion of the full product: The prototype is composed of a robotically articulating laparoscope and VR headset, as well as software and electronics to allow control and visualization through the headset. This portion of the full project was chosen because it demonstrates fundamental engineering design principles needed for an MEng project and could feasibly function as a product on its own.
4

Figure 3: Basic concept visualization

Materials
For this prototype the optical equipment is comprised of an articulating endoscope made by Olympus. VGH has kindly provided a retired endoscope system for use in this project.

All other materials have been purchased or fabricated. 3D printing was used to prototype mechanical systems.

Stakeholders
The stakeholders in this project include surgeons, medical institutes and non-profit medical organizations. Also included are patients who stand to benefit from the use of this medical device in the future.

Project Timeline
From preliminary research to the final project presentation, the project was expected to span a total of 12 months. The following table shows the final project timeline. The self-imposed deadlines laid out here were meant to give a realistic workload and aim for completion in mid-December. The bulk of the project was completed in the Fall 2018 term, when most of the physical prototype was fabricated.

<table>
<thead>
<tr>
<th>Task No.</th>
<th>Task Name</th>
<th>Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full layout of prototype design</td>
<td>01 Nov 2017</td>
</tr>
<tr>
<td>2</td>
<td>Motion detection partial prototype complete</td>
<td>01 Dec 2017</td>
</tr>
<tr>
<td>3</td>
<td>Optical equipment acquired</td>
<td>01 Dec 2017</td>
</tr>
<tr>
<td>4</td>
<td>Graduate Coop Work Term (Jan-Aug 2018)</td>
<td><strong>31 Aug 2018</strong></td>
</tr>
<tr>
<td>5</td>
<td>Optical equipment tested</td>
<td>15 Sept 2018</td>
</tr>
<tr>
<td>6</td>
<td>Video input to PC and VR algorithm functional</td>
<td>01 Oct 2018</td>
</tr>
<tr>
<td>7</td>
<td>Video output to headset functional</td>
<td>15 Oct 2018</td>
</tr>
<tr>
<td>8</td>
<td>Head-movement software complete</td>
<td>21 Oct 2018</td>
</tr>
<tr>
<td>9</td>
<td>Rough mechanical design complete</td>
<td>21 Oct 2018</td>
</tr>
</tbody>
</table>
### Project Timeline

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Final material fabrication complete</td>
<td>21 Nov 2018</td>
</tr>
<tr>
<td>11</td>
<td>Fine-tuning motor control and stabilizing design.</td>
<td>07 Dec 2018</td>
</tr>
<tr>
<td>12</td>
<td>Test rig prepared for demonstration. Report complete.</td>
<td>13 Dec 2018</td>
</tr>
<tr>
<td></td>
<td><strong>Project Completion</strong></td>
<td><strong>14 Dec 2018</strong></td>
</tr>
</tbody>
</table>

*Table 1: EndoVision project timeline.*

### Project Budget

Materials procured for the project included electronics, fasteners, raw materials and motors. The cumulative project costs are shown below:

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Item Cost (CAD)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smraza Microcontroller</td>
<td>16.99</td>
<td>19/10/2017</td>
</tr>
<tr>
<td>MPU 6050 accelerometer</td>
<td>9.99</td>
<td>19/10/2017</td>
</tr>
<tr>
<td>HDMI to USB video converter</td>
<td>123.20</td>
<td>15/09/2018</td>
</tr>
<tr>
<td>SDI to HDMI video converter</td>
<td>45.91</td>
<td>15/09/2018</td>
</tr>
<tr>
<td>SDI cable</td>
<td>5.00</td>
<td>15/09/2018</td>
</tr>
<tr>
<td>NEMA 17 stepper motors (pack of 3)</td>
<td>43.32</td>
<td>05/10/2018</td>
</tr>
<tr>
<td>A4988 motor drivers (pack of 5)</td>
<td>15.66</td>
<td>06/10/2018</td>
</tr>
<tr>
<td>12V 2A power source</td>
<td>24.49</td>
<td>11/10/2018</td>
</tr>
<tr>
<td>5mm pulley (x2) and timing belt</td>
<td>13.48</td>
<td>11/10/2018</td>
</tr>
<tr>
<td>Google Daydream headset</td>
<td>45.00</td>
<td>07/10/2018</td>
</tr>
<tr>
<td>Hose clamps, cable ties, steel rounds</td>
<td>17.24</td>
<td>29/10/2018</td>
</tr>
<tr>
<td>Fasteners, wood screws, screw clamps</td>
<td>28.76</td>
<td>29/10/2018</td>
</tr>
<tr>
<td>5V DV adaptor, power jack, USB cable</td>
<td>28.50</td>
<td>11/11/2018</td>
</tr>
<tr>
<td>Plastic enclosures</td>
<td>6.70</td>
<td>11/26/2018</td>
</tr>
<tr>
<td>Button, DC fan, resistors</td>
<td>8.75</td>
<td>11/26/2018</td>
</tr>
<tr>
<td>Adhesive, Electrical tape</td>
<td>2.81</td>
<td>12/03/2018</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>435.80</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Table 2: Total project expenditures.*

### 4. PROJECT CHAPTERS

The following section is composed of reports written during the project. Chapters are in chronological order and describe the problems faced in the project and their respective solutions as the project progressed.

**Chapter 1 – Sept 16, 2018**

So far, the EndoVision project has just left the conceptualization stage and moved into prototyping. As this project aims to create a working prototype, this will be the last stage. However, a significant amount of work is required to accomplish this, as systems must be designed for each of the following tasks:
1. Take digital video output from the Olympus endoscope video processor and provide useable video input to computer.
2. Receive digital video input to computer.
3. Apply VR algorithm to video in real-time.
4. Send real-time VR video to headset.
5. Obtain live accelerometer/gyroscope data from headset.
6. Receive acceleration/gyroscope data and convert to scope position.
7. Send position data to motor rig.
VGH has been kind enough to lend a full Olympus endoscope kit for this project. The kit includes an Evis Exera II digital video endoscope, light source and video processor, along with necessary cables. This endoscope will provide the video output to be sent to the VR headset.

Figure 4: Simplified concept device function flow chart
A microcontroller and accelerometer-gyroscope combo have also been purchased, and some work has been done to capture the position data in real-time.
Figure 7: Basic Arduino code interfaces with MATLAB to record gyroscope movement.

The Arduino data was originally ready into MATLAB for analysis of the MPU 6050 sensor, however MATLAB will not be used in the final system, as the Arduino can directly control the motors without interfacing with other software.

Chapter 2 – Oct 1, 2018

In the last two weeks, progress has been made on acquiring and processing live video from the endoscope unit:

- Acquired hardware for video connection from endoscope video processor to laptop
- Used Python scripted code with OpenCV library to capture video frames
- Wrote script to display stereo video with barrel distortion for (rough) VR headset display

The first roadblock in analyzing the endoscope video was taking an analogue output from the video processor and converting it to a digital video stream that could be interpreted as a webcam by the PC. This was done using the following:

- SDI video cable
- SDI to HDMI video converter
- HDMI to USB 3.0 video capture card
Figure 8: Endoscope “PC Out” SDI video outlet

Figure 9: SDI to HDMI converter (left) in series with HDMI to USB capture card (right) feeding video signal from endoscope video processor to PC.

The video converters seen above were purchased online to take an analogue SDI video source and
convert it to a digital USB input that a PC can recognize as a webcam.

To properly view the video through a smartphone VR headset, it is necessary to apply a barrel distortion to compensate for the lenses in the VR headset that give the viewer an adequate field of view.

Figure 10: Top down diagram of smartphone VR headset. The optics widen the field of view so that the smartphone can be placed closer to the eyes without being out of focus.
Figure 11: Barrel distortion (left) is used to compensate for VR headset optics.

Figure 12: Live video from endoscope (of a hand) after video is split into stereo video and barrel distortion applied.

Currently, the live video stream is functional but quite slow, with a frame rate of ~1fps. Methods of increasing the display refresh speed are being investigated. The next task is to mirror the PC screen with the screen of the smartphone that will become the headset screen. After that, the distortion values much be adjusted such that the image does not look distorted through the headset optics.

Chapter 3 – Oct 15, 2018

Video Processing Optimization

Since the last project report, the frame rate of the processed video has been increased to an acceptable speed. Where before, the frame rate was at best only ~1 FPS, it is now rendering at the same speed as the camera output (~ 60 FPS). This was done by revising the Python code to use matrix mapping operations to distort the video instead of a pixel-by-pixel nested “for” loop. Python (Using the OpenCV library) is optimized for matrix operations and has internal functions to access and change pixel values orders of magnitude faster than using a nested for loop.

This step was critical in creating a working video signal which can be viewed through a head-mounted display (HMD).
Figure 13: Python script using “remap” function to assign image pixels to different locations based on a radial distortion function.

The OpenCV remap function draws pixel values from a source image and moves them based on a predefined matrix maps. It uses linear interpolation to guess pixel values between image pixels.

The operation used before this solution, was to loop through every pixel in the image using a nested for loop, and copy the pixel value to a new location defined by a barrel distortion function. The for loop is still used to initialize the map, however after the first loop, the remap function is now used for increased speed.

Video Signal to HMD

To view the video with an HMD, a smartphone VR system is used. The video output from the Python script is displayed in real-time on the PC screen, and a free screen-mirroring app (SpaceDesk) is used to show the same video on the screen of a Google Pixel 2 smartphone. This app uses a USB3.0 connection between the PC and smartphone to send the video signal.
A Google Daydream VR headset in combination with a personal smartphone (Google Pixel 2) was chosen as the HMD, as this was the most cost-effective option. The Daydream is simple to use and works well with the Google Pixel smartphones.
The smartphone is then secured by the Daydream headset, which holds it at an appropriate distance in front of the lenses.

The video signal originating in the endoscope is now effectively viewable using the Google HMD.

3-Axis Gyroscope Angular Data

The MPU6050 3 axis gyro sensor was purchased several months ago, and some work has already been done to obtain an angular yaw, pitch and roll data output. Only yaw and pitch data are needed, as the endoscope system will only have two axes of rotation.
The gyro sensor works well, and gives a very precise, repeatable and fast-responding relative angular position measurement. The Arduino microcontroller powers the MPU6050 and reads the returning data as an I^2C communication device.

Figure 17: Roll, pitch and yaw rotations around axes.

Figure 18: MPU 6050 connected to an Arduino microcontroller (not shown).
One downside of using a gyroscope magnetometer for yaw data (left-right head movement) is gyroscope drift: Drift occurs during the first 15 seconds after the gyroscope is activated and appears as a slowly increasing yaw angle. After 15 seconds, the drift stops and the Arduino program automatically resets both yaw and pitch angles to zero.

This means that the endoscope system requires a 15 second “warm up” period for calibration after initiation. After the initial calibration, the gyroscope system runs flawlessly.

**Stepper Motors and Controllers**

Two NEMA 17 stepper motors were purchased to drive the angular position of the endoscope knobs, thus controlling yaw and pitch motion of the camera tip. These motors are used in many 3D printers and have high torque and angular accuracy.

The motors have a maximum torque of 0.59 Nm and a step angle of 1.8 degrees. If necessary, ½, ¼, ⅛ or even 1/16 step increments can be taken with the NEMA 17. This will likely be unnecessary however, as the pulley system will step down the angular increment seen by the endoscope camera even further.
Figure 20: NEMA 17 bipolar stepper motors. One is used for controlling yaw angle, the other for controlling pitch angle.

The motors run on a 12V - 2A power supply and are controlled by two A4988 motor drivers. The motor drivers are in turn controlled by the Arduino microcontroller and regulate pulses of the 12V power supply to the NEMA 17 motors as dictated by the Arduino code.

The motors are controlled by supplying rotation direction and a number of steps command to the motor controllers.
With the setup above and an Arduino script; pitch and yaw angles are obtained from the MPU6050, then the current motor positions are compared to the pitch and yaw angles, and the difference in motor steps is sent to the A4988 controllers. Pulses are sent to the NEMA 17 motors which rotate forwards or backwards until the difference is zero.

**Pulleys and Timing Belt**

To control the handheld endoscope knobs with the stepper motors, some custom interface will be necessary, as the knobs are designed to be an ergonomic handheld interface.

The use of pulleys and a timing belt will be explored, as they will likely allow for more mating tolerance than gears.

The off-the-shelf pulleys and timing belt below have been purchased. They were selected with a 5mm bore to fit the NEMA 17 motor shaft. The timing belt width is 6mm and the pitch is 2mm.
Custom Pulley Design

As the knobs on the endoscope handle are meant for handheld operation, a custom handle-end pulley must be designed to connect the motors to the drivetrain for camera articulation.

![Image of custom pulley design](image)

**Figure 22: Drawings and specs of off-the-shelf pulleys purchased.**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Calculated steps per mm for firmware</th>
</tr>
</thead>
<tbody>
<tr>
<td>For belt type / pitch</td>
<td>GT2 / 2mm pitch</td>
</tr>
<tr>
<td>Number of Teeth</td>
<td>20</td>
</tr>
<tr>
<td>Pitch Diameter</td>
<td>12.7mm / 0.5&quot;</td>
</tr>
<tr>
<td>Outside Diameter</td>
<td>12.2mm / 0.48&quot;</td>
</tr>
<tr>
<td>1.8&quot; stepper motor, full step</td>
<td>5</td>
</tr>
<tr>
<td>1.8&quot; stepper motor, 1/8 step</td>
<td>40</td>
</tr>
<tr>
<td>1.8&quot; stepper motor, 1/16 step</td>
<td>80</td>
</tr>
<tr>
<td>1.8&quot; stepper motor, 1/32 step</td>
<td>160</td>
</tr>
</tbody>
</table>

![Image of custom pulley design](image)

**Figure 23: Endoscope handle with Up/Down knob on the bottom and Left/Right knob on top. Pulleys will have to be custom made to fit over each of these knobs.**

The attachment design will use a steel plate secured onto the top of each knob. The custom pulley can then be attached to the steel plate as shown in the SolidWorks assembly below.

Custom pulleys will be printed in PLA plastic with a 3D printer.
Holes will be manually drilled in the attachment plate and small straps will be used to connect the plate to the knob, preventing loose rotation.

This design is still in progress and is likely to be updated in the next project report.

Chapter 4 – Oct 29, 2018

Motor Rig Chassis

The purpose of the motor rig chassis is to hold the endoscope handle in position allowing the stepper motors to connect to the articulation knobs via timing belt.

The prototype chassis is constructed with plywood with steel brackets attached to hold the stepper motors in place. Steel hose clamps with rubber inserts are used to hold the endoscope handle firmly, without marking the surface.

One stepper motor is mounted on each side and set at different levels. One motor will control the right/left (yaw) articulation, and the other will control the up/down (pitch) articulation.
Figure 25: Top and side views of the motor rig chassis.

Pulley Attachment Disks

The pulley attachment disks are meant to fix the pulley onto the ergonomic handles of the endoscope. They are machined from 1mm aluminum sheet and have a slot on one side for insertion onto the endoscope knob.

The disks will have holes drilled and zap straps will be threaded through to fix them to the ergonomic handles. The 3D printed pulleys will then be attached to these disks using small fasteners.

Figure 26: Solidworks part (left) and fabricated aluminum attachment disk (right).
3D Model for Printing

The final part needed to connect the stepper motors to the endoscope knobs to control articulation is the 3D printed pulley. The pulley has been designed using Solidworks to have the same pitch (p = 2mm) as the off-the-shelf pulleys and timing belt.

The pulleys will be printed in two parts as shown below and attached with epoxy before being mounted on the attachment disks. The pulley has overhanging features, which require supports to print in traditional 3D printers. These supports can be difficult to remove after printing and result in surface roughness.

One way of avoiding this issue with supports is to separate the part and print two parts separately (which do not have overhanging features).

A tongue-and-groove connection was designed to make part alignment easier after printing.
Figure 28: CAD model of printed pulley. Pulley is printed in two parts (left) and attached with epoxy (right).

Figure 29: CAD model showing overhanging features.
Next Steps

Currently, the project cannot progress without the 3D printed pulley component. Multiple printing services are being explored to have the part made quickly so the project can continue.

After the part is acquired, holes must be drilled in the connection disks for fasteners. After the pulleys are mounted onto the endoscope knobs, the timing belt must be cut into two lengths and connected to form two loops. The timing belt can then be placed between the stepper motors and the endoscope handles.

After assembly of the motor rig, testing of the full motor control system may begin.

Chapter 5 – Nov 11, 2018

Motor Pulley Redesign

Initially, the design to attach the motor pulleys onto the ergonomic handles of the endoscope involved the use of machined aluminum plates as seen below. The plates were to have holes drilled and plastic straps passed through the holes to attach to the fingers of the handles. It was immediately discovered that this system did not work, as the attachment of the plates to the handles was too difficult and caused excessive friction.

Another problem was identified in that the pitch of the pulley teeth was not perfectly aligned with that of the timing belt, meaning that some slippage was occurring.
Both of these problems were addressed in the following redesign:

![Image of initial pulley attachment design using aluminum plates.](image1)

*Figure 31: Initial pulley attachment design using aluminum plates.*

The pulley mounting was redesigned to use only 3D printed parts that fit directly over top of the ergonomic handles. This approach was much simpler to fabricate, as 3D printers can easily create complex shapes that are impossible to achieve in machined aluminum.

![Image of version 2 of top (left) and bottom (right) printed pulleys.](image2)

*Figure 32: Version 2 of top (left) and bottom (right) printed pulleys.*

The pulleys were designed to fit directly over the ergonomic handles. The top pulley has holes for screws to clamp down on the handle. The bottom pulley has holes for plastic straps which wrap around the fingers of the bottom handle.
Figure 33: Pulley printing orientation. Single-piece pulley components.

Top and bottom pulley components were designed this time to be printable in a single piece for additional strength, meaning the elimination of sharp overhangs near the pulley teeth. A 45° overhang does not generally require supports while printing.

Figure 34: Solidworks assembly of the V2 pulleys over the ergonomic handles.

The pulleys printed without issue and achieved a snug fit onto the endoscope handles. The clamp screw held the top pulley in place and the plastic straps had enough clearance underneath the bottom pulley, as seen below.
Figure 35: Assembly of physical parts onto endoscope handle.

Motor Rig Fabrication

The fabrication of a working motor rig has been completed and is seen below. The rig consists of a plywood base and supporting structures to hold the motors in the correct orientation to apply a torque to each of the endoscope handles without slipping.

Figure 36: Assembly of motor rig with printed pulleys and timing belts.

The hose clamps allow adjustment of the position of the endoscope handles to provide adequate tension in the timing belts.

Electronics Board Re-fitted

The electronics have been condensed and refitted so they are now on a single board, which can be moved without fear of breaking electrical connections. This board will be made more robust and be given an enclosure for additional protection.
Figure 37: Electronics board initial layout
Figure 38: Electronics schematic of the dual stepper motor system controlled by a microprocessor

Gyroscope Attachment

The positioning of the gyroscope onto the VR headset is essential to get the pitch and yaw angle data to drive the motors. The MPU6050 gyroscope/accelerometer sensor was mounted on the Google Daydream headset using needle and thread (because the headset is fabric). This holds the sensor snugly for now, however if time allows, more permanent mounting options may be explored.

A recycled video cable was used to connect the MPU6050 to the Arduino microcontroller, where the angle data is processed.
Figure 39: MPU6050 rewired and attached to headset.

**Working Prototype**

The prototype now has full functionality. Rotation of the headset in the left/right and up/down causes the endoscope to articulate to match the movement.

Figure 40: Demonstration of left/right articulation of endoscope.
Electronics Enclosures

Two enclosures were created to protect the electrical components and to increase ease when plugging in connectors.

Below is the Arduino/breadboard enclosure. A DC fan was added to the top of this enclosure, as the stepper motor controllers can generate excess heat after a long duration of motor activity.

An on/off button was added to the motor power supply for additional ease of use.

Another enclosure was fabricated to house the video conversion electronics. These are simply the two video converters which take in an analog SDI signal and output a USB 3.0 signal that a PC can read and analyze in real time.

To reduce clutter and for protection, these electronics were housed in a separate enclosure.

Ideally, all electronics could be housed in one compact enclosure, but due to concerns of EMI (electromagnetic interference) and due to budget constraints, the enclosures were kept separate for this prototype.
Demo Stand

For the use and demonstration of the endoscope, it is useful to have the up/down and left/right of the scope movement match the up/down and left/right directions relative to the ground. The endoscope was designed to be held during operation and twisted, so the up/down angle is not perpendicular to the ground when laid flat.

A stand was designed to hold the endoscope at the correct angle so that left/right and up/down articulation with the headset causes the same articulation of the endoscope relative to the user.
Figure 43: Motor rig stand to hold endoscope handle in correct position. “Up” articulation results in upwards motion.

Reset Button

A “reset” button was also added, giving the user the capability of adjusting the orientation of the headset, then bringing the view back to center. This was deemed necessary, as the articulation of the scope is limited, and users will need to put on the headset and bring the view back to a zero position before continuing.

Ideally, a “home” (zero position) button would be placed on the headset itself, so a user could stand in a comfortable position, then set the view to “home” before continuing to view. The button was placed instead on the breadboard, as this is meant to be a proof of concept demo.
Figure 44: Endoscope angle reset button.

Seen below is the effect of the reset button on the target up/down (pitch) and left/right (yaw) motor position data.

Figure 45: Reset button used to bring pitch and yaw motor positions back to zero. The green and yellow
plots show the target motor position and the blue and red show the actual position.

Angle Limits Defined

To prevent damaging the motor rig or the endoscope, the physical limits of the endoscope’s articulation were defined. A simple program was written to step the motors forward in small increments and it was noted that at both ends of the up/down and left/right motion, slippage of the timing belt on the motor pulleys occurred. The motor angle limits were defined to prevent pulley slippage due to excess torque.

<table>
<thead>
<tr>
<th>Movement Direction</th>
<th>Maximum Motor Motion (steps from zero position)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up/Down (pitch angle)</td>
<td>+/- 245</td>
</tr>
<tr>
<td>Left/Right (yaw angle)</td>
<td>+/- 165</td>
</tr>
</tbody>
</table>

The angle step limit for the yaw is seen to be smaller because of physical torque on the “left/right” handle of the endoscope being greater than that of the “up/down” handle.

Figure 46: Implementation of yaw angle motion limit at +165 steps.

After implementation of the angle limits, it is now safe for users to move the headset in any direction without damaging the motor rig.
Step Size Refinement

It was noted that the motion of the headset felt somewhat course at the outer edges of the motion. To fix this, the step size was reduced from 2 to 1 steps at a time, meaning slightly slower response but better accuracy and smoother motion.

![Graph](image)

*Figure 47: Pitch (blue & green) and yaw (orange & red) angle motion sent to motors as step commands.*

Problem 1 - Erratic Noise in Angle Data

The largest problem being faced at this stage is a problem of unpredictable noise arising in the angle data coming from the MPU6050 gyroscope/accelerometer. At times the data becomes corrupted and fluctuates between a maximum and minimum, causing sporadic movement in the motors.
Figure 48: Unpredictable noise dominates pitch and yaw data from the MPU6050.

The cause is suspected to be a serial communications error due to time-consuming computations performed by the microcontroller. Currently the only fix when this arises is to restart the system.

Solutions are currently being explored for this issue.

Problem 2 – Backlash Hysteresis

The second problem currently being faced is the issue of mechanical slack (backlash hysteresis) in the endoscope. Since the scope is meant to be adjusted by sight and feel, it was not designed to have a constant output in articulation for each input step into the rotation of the handles (ie. the handles can be slightly rotated back and forth before any articulation in the scope occurs).

The backlash has been calculated for the pitch and yaw in the same way the angle limits were defined:

<table>
<thead>
<tr>
<th>Movement Direction</th>
<th>Endoscope Backlash (steps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up/Down (pitch)</td>
<td>40</td>
</tr>
<tr>
<td>Left/Right (yaw)</td>
<td>35</td>
</tr>
</tbody>
</table>

For example, when changing movement direction in pitch angle, the motors must step an additional 40 steps before the slack in the system is taken up and motion of the camera is seen.
Solutions to this problem are currently being explored.

Chapter 7 – Dec 03, 2018

Neither problems 1 or 2 from Chapter 6 were completely eliminated; however significant progress was made on both. At this point the prototype can be considered finished for demonstration purposes.

The electronics layout of the motor rig was fully inspected, and it was found that the motors were operating at a higher current than necessary. It is possible that current spikes caused by motor activation caused a voltage fluctuation through the breadboard which resulted in an inconsistent power input to the accelerometer. This could have resulted in the sporadic noise seen in figure 48.

The A4988 motor controller has a built-in potentiometer to limit the current sent to the motors. The potentiometer was adjusted with the motors on until the supplied current gave just enough torque to articulate the endoscope.

![A4988 Stepper Motor Controller with Built-in Potentiometer](image)

*Figure 49: A4988 stepper motor controller with built-in potentiometer.*

The problem of backlash was also characterized more closely: The mechanical slack was found to be largest when moving through the 0° point in both the left/right and up/down articulation. This was found to be a larger problem than the backlash as described in project update 6.

The problem of mechanical slack was addressed by adding an angle-dependant step multiplier. Two bounds were chosen around the 0° point for each motor, and when operating between those bounds, the motor would step “X” more times for each degree of rotation of the headset. This means less head movement is needed to articulate the scope in the region most affected by mechanical slack.
5. DISCUSSION

The project can be considered successful, as a working proof-of-concept system has been created, which can direct the surgical FOV with head motion alone. During the project, however, some major roadblocks were encountered:

**Processing Speed**

Initially, the Python script used a nested “for” loop to go through each frame pixel-by-pixel and apply the barrel distortion. That was found to give a very slow frame rate (<1 FPS). This was solved by utilizing the “remap” function in the OpenCV library. This function uses matrix operations to complete the distortion orders of magnitude faster. The frame rate after using the “remap” function was ~ 60 FPS.

**Sensor Noise**

Another challenge faced in this project was the problem of randomly arising sensor noise from the MPU 6050. At unexpected times, the angle data would be replaced by random noise and the only fix was to restart the system. A solution was found to this problem: The potentiometers controlling the maximum motor current were turned to limit the motors to the minimum required power. This both reduced the frequency of the noise problem and reduced the motor noise.

Due to the nature of the problem fix, the problem likely arose due to electrical instability of the breadboard, leading to spikes in current to the MPU6050 sensor, ultimately resulting in sensor noise.

**Backlash Hysteresis**

The final major problem in the prototype design was the mechanical slack (backlash) in the endoscope system. The endoscope was not meant to have a linear relationship between turning of the handles and articulation of the scope, and this is noticeable when wearing the headset and directing the FOV.

No adequate solution was found for the problem of backlash, however the sensitivity of the entire system was increased, and this made a difference when articulating the scope, as it helped to reduce the lag time.

There are many considerations as this project progresses: Moving forward in this project, it will be important to adequately classify the physical system to optimize the movement of the scope. Streamlining of the physical device is important for clinical use. Removing as much of the mechanical slack as possible from the system will be key in its performance. Minor imperfections can be accounted for in the controlling software.

Using an HMD system in the operating room is currently seldom done, as some surgeons find the systems cumbersome, and want peripheral view as they perform a surgery. This should also be considered as the project moves forward, to ensure the product is one that surgeons find comfortable and intuitive.
6. **RISK MITIGATION**

Now that a working prototype of the endoscope system is complete, some thought must be given to the risks of a finished medical device moving forward. To sell medical devices in Canada, all organizations must follow Canada’s Medical Devices Regulations (SOR/98-282) to ensure quality of performance and manufacturing\(^9\). To sell devices in the United States, regulations set by the FDA must be met\(^{10}\).

Some of the most important risks in the regulatory approval process are as follows:

- **Patient harm due to endoscope use or articulation.** The device must be proven through rigorous testing to be of no greater harm than a standard endoscope controlled by hand.
- **Inability to demonstrate consistent device results.** All devices must meet minimum standards for dependable performance and durability. Organizations unable to demonstrate these minimum standards may have regulatory approval revoked, and may face a device recall.
- **Inability to demonstrate safe and consistent device manufacturing procedures.** All regulatory bodies require detailed documentation showing safe and reliable manufacturing. In addition, organizations such as the FDA routinely audit medical device producers to ensure the presence of quality systems in device production.

Other risks to the project (besides regulatory approval) include:

- **Improper understanding of surgeons’ preferred methods of communications and demand for improved visualization.** Mitigation includes continued research and conversations with practicing surgeons to ensure the need for the product exists.
- **Lack of trust in the device among healthcare professionals.** Mitigation for this risk involves conducting in-depth studies to confirm an objective healthcare benefit resulting from use of the product.
- **Lack of high-speed internet in remote/developing regions.** This risk is unavoidable and will limit the capabilities of telementoring. Mitigation involves setting up the surgical system first in areas with the required internet speeds.

7. **PROJECT CONTINUATION**

As the project moves forward, further development is necessary before the device is a viable product. Some remaining tasks are shown below:

- Completion of the telementoring system design, allowing real time viewing and audio/visual feedback from users over the web.
- Streamlining of physical device design.
- Detailed design study to ensure compliance with medical device quality standards.
- Augmented Reality tools may be implemented to enhance the surgeon’s ability to identify structures or allow more advanced visual assistance from remote specialists.
- 3D medical images may be overlaid to help guide surgeon.
- More dexterous laparoscopic surgical instruments can be designed for further ease of use.

8. CONCLUSION

The prototype system has been completed and the concept has been proven viable. The project demonstrates that a system using free software, simple electronics, off-the-shelf components, 3D printed parts, and a standard video endoscope can be created for intuitive endoscopic visualization. Alone, it is a small step forward in medical technology, but the potential benefits are far-reaching:

With a lack of doctors and surgeons worldwide and an ever-growing population, it is paramount that existing healthcare professionals use their time efficiently. This project aims to develop an inexpensive system to augment a surgeon’s ability to diagnose and treat a patient during MIS by improving visualization for the surgeon and providing a platform for real-time communication with other specialists. In the long term, the project aims to expand the reach of minimally invasive procedures by increasing surgeon accessibility and reducing risk to patients.
9. REFERENCES


7 Harvard School of Public Health: More than 2 billion people worldwide lack access to surgical services. ScienceDaily. 2010


