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COMPUTER CONTROLLED HYDRAULIC NANOMANIPULATOR

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ABSTRACT

Nanomanipulators are high-precision positioning instruments used in conjunction with high magnification optical and electron microscopes to interact with objects on the nanometer scale. Biomedical science can make use of such equipment to elucidate the behavior of individual living cells at the nanoscale and to help develop advanced diagnostic and therapeutic modalities for disease. However, obtaining access to such instrumentation is often difficult due to geographical or financial limitations. The high cost of pre-existing commercial nanomanipulators, typically in the tens of thousands of dollars, greatly restricts the ability for educational or research organizations to benefit from such an instrument. Described here is the development of a nanomanipulator with remote access capability which can be manufactured for under $2,000. The prototype nanomanipulator consists of a hydraulic drive system and a three axis Cartesian manipulator. The drive system converts the rotational motion of a stepper motor with a planetary gearbox into linear actuation of hydraulic cylinders. Movement resolution comparable to commercial manipulators is achieved through the utilization of hydraulic advantage. A simple graphical user interface (GUI) enables users to remotely access and control the instrument through a free software package. Instrument control is available using standard computer mouse and keyboard devices, and real-time visual feedback is provided from a camera device attached to the microscope. The computer-controlled hydraulic nanomanipulator allows students and researchers around the world increased access to nanoscale science. enriching educational experiences and providing increased opportunity for further research. In comparison to pre-existing, commercially available nanomanipulators, this project will provide comparable manipulation performance and robust remote access features at just a fraction of the cost.

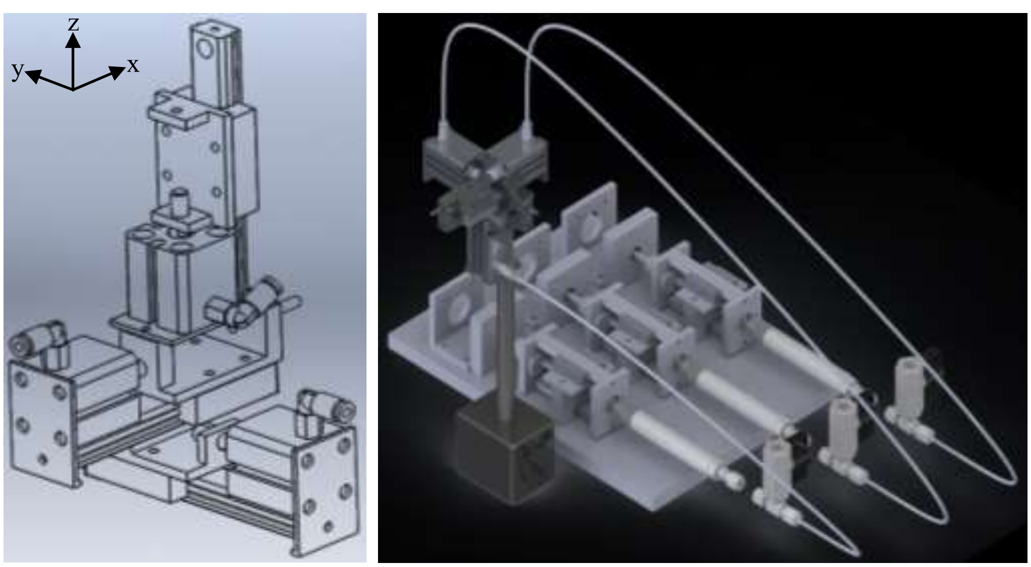

Figure 1: CAD model of manipulator system, with a system assembly drawing using the old mounting configuration

INTRODUCTION

The goal of this project is to build upon the work of two previous Multidisciplinary Senior Design teams (P13371, P12371) [1, 2]. The previous project's hydraulic pump and electronic motor control were deemed functionally robust; therefore this project focused to improve the manipulator subsystem and introduce remote control capability. The high-level system design inherited from project P13371 continues into this project as the overall subsystem design and arrangement.

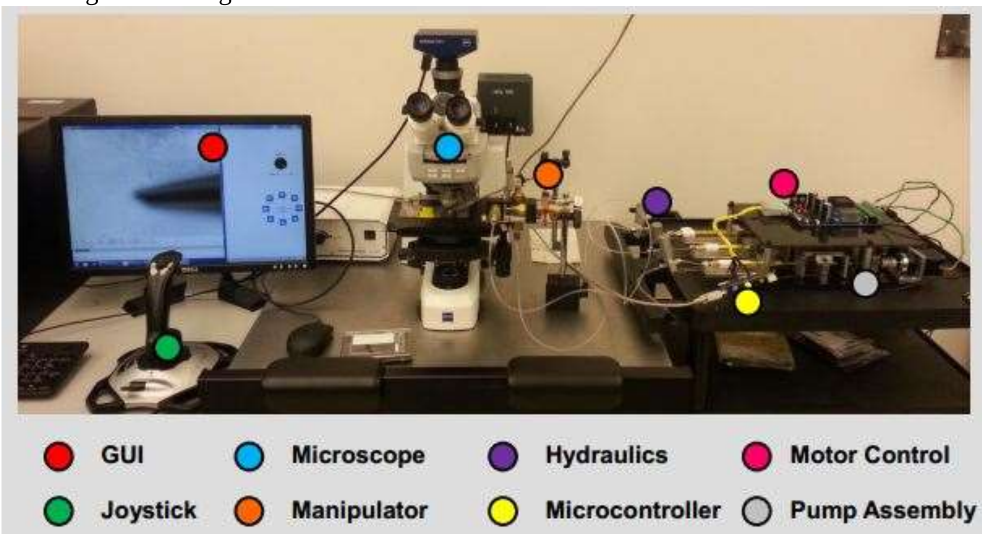

Figure 2: The nanomanipulator system and its subsystems. [2]

The manipulator subsystem consists of the three hydraulic cylinders located closest to the pipette tip. This subsystem is responsible for the Cartesian movement of the pipette. The pump assembly subsystem's pistons provide hydraulic action for each Cartesian axis, allowing for independent movement of the manipulator subsystem's axes. The pump assembly subsystem consists of a lead screw driven by a stepper motor for each axis, independently, which in turn compresses or decompresses its respective piston.

The system produced by team P13371 was tested by team P13375. Results comparable to those produced by team P13371 were not obtainable. For example, the system was found to have backlash of approximately 30 revolutions in the x-axis while this specific axis had shown the most reliable performance in testing performed by team P13371. The system also did not appear to be air tight. A significant volume of air entered the system within some hours of being filled or utilized. This hydraulic leak was severe to the point that it required the hydraulic system to be refilled daily in order to obtain acceptable motion. Another aspect of the original system's performance found to be unacceptable was the manipulator speed of movement. This was due to the desired speed specification of project P13371 having been below the marginal value specified by the project customer. The original system overall had a significant amount of drift (i.e., backlash) in all movement axes and was physically bulkier than the customer desired. For comparison, a commercially available Eppendorf nanomanipulator was tested and shown to perform without backlash, drift, or required maintenance after use.

PROCESS

Project planning and design guidance was provided by the Multidisciplinary Senior Design Center at Rochester Institute of Technology. System requirements and specifications provided by the project customer were gathered and evaluated against the inherited project. This was done in an effort to determine which potential changes would provide the most significant performance impact. The specifications were iterated upon and adjusted through continued discussion with the project customer. The capability to allow for the nanomanipulator to be controlled remotely by standard computer input devices via the Internet was added. The range of motion required was reduced to more closely reflect the size of the stage under magnification. The House of Quality technique was used to analyze the determined system specifications in order to ensure they would meet the requirements of the project customer. This technique involved ranking specifications based upon the customer requirements they would satisfy.

A Pareto chart was generated and this has been included in Figure 3. The most important specifications were shown to be ease of use, calibration, video latency, manipulator backlash, control latency, limit of travel in each direction, resolution, and input device control. These eight specifications satisfy 65% of the project's requirements.

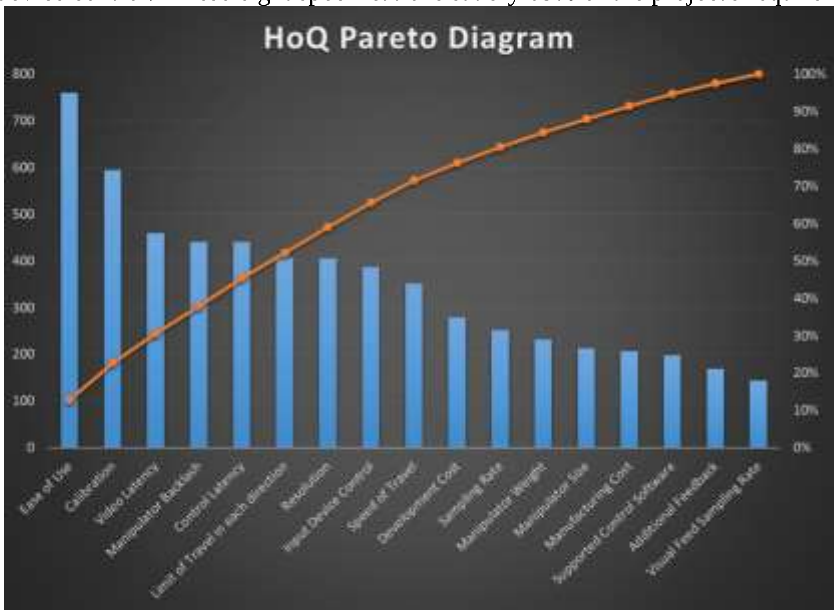

Figure 3: Project specifications ranked with a Pareto chart.

A system architecture combining the mechanical and software subsystems was proposed to meet the specifications of the nanomanipulator system. A block diagram outlining the proposed system architecture is included in Figure 4.

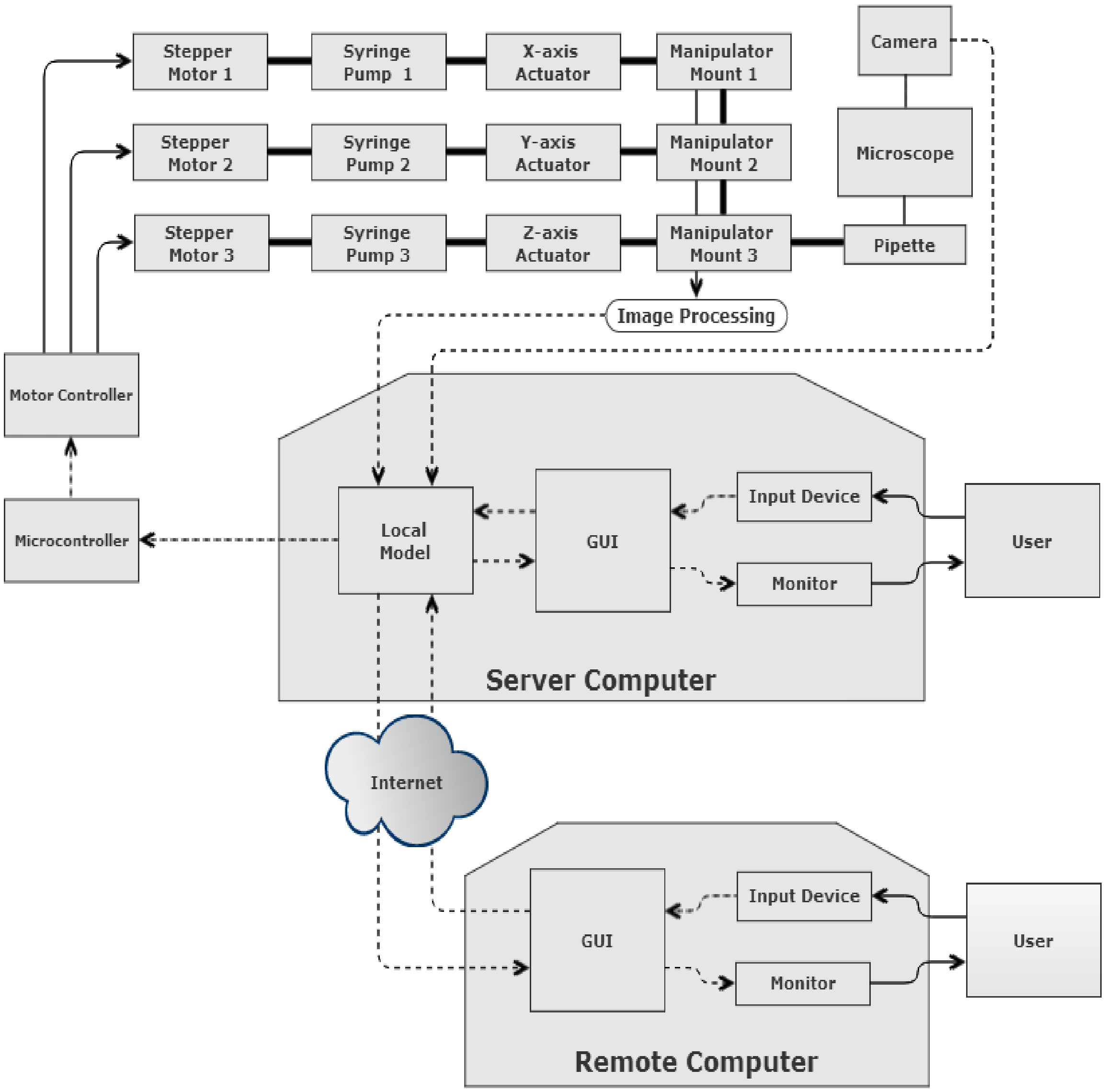

Figure 4: The proposed nanomanipulator system architecture.

Mechanical Subsystems Design:

Several different concepts were evaluated to satisfy customer needs. The main issues with the current system were determined to be severe backlash, system drift, and low speed of movement of the manipulator. The problematic need to refill the hydraulic fluid after each use was also an area planned for improvement. It was determined through system testing that all backlash was generated in the manipulator subsystem. No backlash was observable using a micro-sized scale at both the lead screw and the pump assembly. The fishbone diagram included in Figure 5 provides a breakdown of the system problem areas that were identified for testing, as well as some testing results.

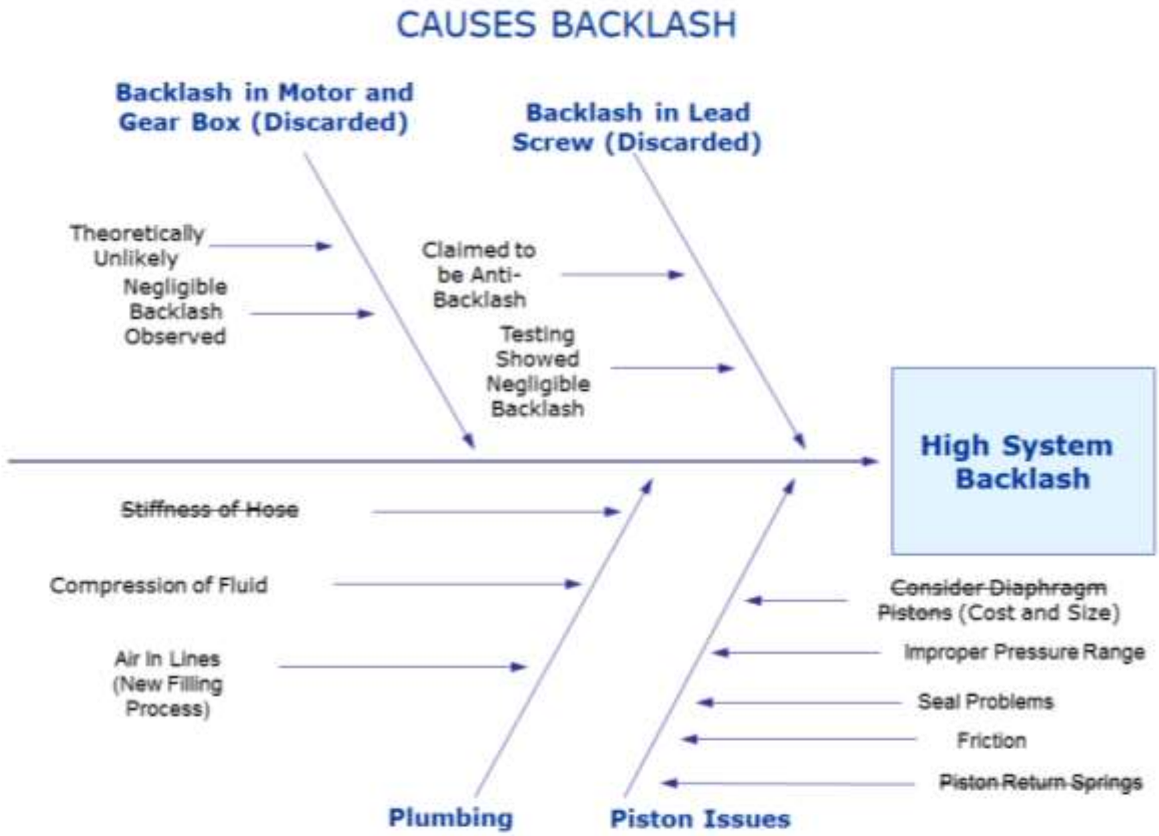

Figure 5: A fishbone diagram highlighting possible areas of improvement on the original system.

Through testing and observation of the inherited manipulator system it was determined that the areas that would provide the most significant results upon improvement were those of the manipulator subsystem and hydraulic pump components. Complete replacement of compression fittings, tubing, and manipulator cylinders were determined to have the largest potential for improvement. These measures ensured there were would be no damaged fittings or hydraulic lines, which is a potential source of fluid leakage. New low friction cylinders were proposed to decrease the system backlash. Diaphragm pistons were considered as they are often used in commercially available nanomanipulators, however due to cost and the lack of availability of pistons in the size required, this choice was eliminated. A Pugh matrix was used to determine the best option for increasing speed between replacing manipulator cylinders, motors, gear box and a new lead screw which was used as the comparison. Replacing either the motors or gear boxes received a negative score, while replacing the cylinders received a score of zero in comparison to replacing the lead screw. The pistons were selected to be replaced due to their lower system integration cost and the potential to improve system friction as well. Pistons in the size range required were difficult to find and the team was unable to find hydraulic, low friction pistons that were acceptably sized and sensitive enough for this system. A Pugh matrix was again used to evaluate the best piston option from 4 new options. The most significant Pugh categories were considered to be reducing friction, providing precise control, and operating in the appropriate pressure range. Pneumatic pistons were thus considered and the MQP10-10s was selected. These pistons are pneumatic, very low friction pistons, and are operable within desirable pressure ranges. The supplier informed the team that the MQP10-10s cylinder would not leak at the pressures the system produces and that they would not rust. Replacing the system compression fittings with new push to connect fittings would allow for easier assembly and highest component compatibility. The team concluded that replacing the system compression fittings and selecting improved non-friction cylinders (MQP10-10s) would reduce system backlash, increase system speed, and significantly improve upon the mechanical system.

The MQP10-10s pistons have a bore diameter of $10\,mm$ and a stroke of $10\,mm$. The $10\,mm$ stroke length allows the systems to meet the minimum stroke specification of $0.25\,cm$. The diameter of the piston bore impacts both the speed and resolution of the nanomanipulator as shown in Equation 1 [1, 2] and Equation 2 [1, 2]. Equation 2 represents the speed of the nanomanipulator, which is a function of the rotational speed of the stepper motors w_{motor}, the linear conversion of the lead screw L, and the hydraulic ratio H. The proposed system produced a theoretical speed of $0.1056\ mm/s$. This is an improvement upon the inherited project speed performance of $0.04\ mm/s$ obtained through testing. Both values are below the project speed specification of $0.5\ mm/s$; however this iteration provides significant improvement, and in discussion with the project customer this seemed satisfactory, particularly while at high microscope magnification. The proposed system produces a resolution of $104.67\ nm/step$. The previous system had a resolution of $54\ nm/step$. The specification for the project was a resolution of $100\ nm/step$ or less. In discussion with the customer it was determined that a resolution of $104.67\ nm/step$ was acceptable.

$$H = \frac{D_{manipulator-piston}}{D_{pump-piston}} = 1.10$$ **Equation 1**

$$Manipulator\ Speed = L * w_{motor} * \frac{1}{H} = 0.1056\ mm/s$$ **Equation 2**

$$Resolution = L * P * G * \frac{1}{H} = 104.88\ nm/step$$ **Equation 3**

As shown in Equation 2 an increase in the hydraulic ratio results in a lower speed.

Equation 3 [1, 2] shows that resolution is a function of the linear conversion of motion in the lead screw L, the pitch of the lead screw P, the gear ratio G, and the hydraulic ratio H. Modification of the hydraulic ratio may be performed to further refine the resolution. It may be seen that the speed and resolution are inversely related, and that a change in the hydraulic ratio would result in opposing changes in each of these specifications. A balance had to be chosen between desired speed and resolution.

The cylinders selected for the new system did not contain a return spring to assist with bringing the manipulator tip backward when the pressure in the pump subsystem piston is decreased. The new system was designed to incorporate a return spring outside of the cylinder for both the x-axis and the y-axis, and uses gravity in the z axis. A model of the system is included in Figure 1 on the first page of this document. The spring was selected by determining the required minimum k from the relationship that the force is equal to $-k$ times the distance traveled. The force was due to the weight of the system components being moved. The required k was analytically determined to be 0.76 lb/in or above, however a variety of k values would be acceptable because the distance of compression could be adjusted in the system. Two springs were ordered one with a k of 3.57 lb/in and one with a k of 0.76 lb/in. The spring with a higher k was found to work best in the MQP system.

The system pressure was found to not exceed $17\ ps$ while the cylinders are rated for $0.4\ psi$ to $100\ psi$. The system torque was found to be $14.6\ N$ and the stepper motors were tested up to $70\ N$ without any issues.

Piston Cylinder (MQP Version) Leakage Issue:

During component testing it was determined that the cylinders leak around the piston due to the lack of an o-ring seal and the use of a metal seal. This was an unexpected issue because the supplier had confirmed with the team that there would be no leakage at the pressures the system experiences with water. The team took care to discuss any foreseeable issues with the supplier because the cylinders were designed for use in a pneumatic system and this implementation is hydraulic. The team was assured that the cylinders would not leak or rust, which contributed to the team's decision to use these cylinders. The system using MQP cylinders leaks when sufficient pressure is applied by the return spring to keep the system from taking in air and producing backlash. The system experienced jumpy motion, high backlash, lower than anticipated speed, and the system needs refilling after use due to the leakage from the MQP cylinders. The previous system from team P13371 also needed refilling after each use and the MQP system has an improved filling method that is explained in the user manual and shown in a video found on the team website. Suggested methods to reduce leakage were to use insoluble grease around the piston, which was not effective. Oil was used in the system which did not stop leaking, but did complicate the filling process. The use of an o-ring outside the cylinder and secured in place with a face plate stopped the leakage, however it produced considerable backlash due to stick slip from the o-ring, and there was considerable potential for misalignment. The team then moved to exploring new cylinder options, and selected CQS cylinders. Their design is very similar to the MQP system however they contain an internal o-ring seal and are double acting. The second port can be sealed with a bolt and pipe tape, which converts the cylinders to a single acting model. The CQS cylinder also do not contain an internal spring return, however the same method as used with the MQP cylinder is effective in providing an external spring return. A k of 0.76 lb/in was found through testing to be acceptable. The MQP system required only minor adjustments, such as a new mounting plate to account for the smaller profile of the CQS cylinders, however a revised mounting system was designed to offer greater system stability. During testing the CQS cylinders showed no leakage at the systems maximum pressure at full stroke, as well as improved system performance parameters as shown in table 1 in the Results and Discussion section. After testing the team decided to move forward with the CQS cylinders.

Theoretical values for the CQS system were computed as shown below using the equations discussed previously. The CQS cylinders produce a greater hydraulic advantage due to a larger piston bore diameter of 12mm. This increased hydraulic ratio produces a lower speed and a refined resolution.

$$H = \frac{D_{manipulator\ piston}}{D_{pump\ piston}} = 1.33$$ **Equation 4**

$$Manipulator\ Speed = L * w_{motor} * \frac{1}{H} = 0.088\ mm/s$$ **Equation 5**

$$Resolution = L * P * G * \frac{1}{H} = 86.74\ nm/step$$ **Equation 6**

The team is also considering the use of single acting CQS pistons that contain an internal spring return. These pistons have the same bore diameter and stroke length and should work well in this application. They produce the same speed and resolution. These pistons would not require an external spring return device, thus simplifying the design to a degree. This option still includes an o-ring seal to prevent leaking.

Software Subsystems Design:

The three major software subsystem components of the nanomanipulator are the computer input controls, the graphical user interface (GUI), and the remote control access. The existing GUI does not meet required specifications and is replaced by a modified version of Nicholas Hensel's MATLAB-based GUI developed for controlling an Eppendorf manipulator[3]. The adaptations consist of adding serial communication to the nanomanipulator control subsystem, Internet-based remote control, real-time visual microscope camera feedback capability, and implementing software-driven manipulator calibration.

The existing motor control subsystem involves a Freescale microcontroller programmed with embedded C code to interface with the system GUI via an RS-232 serial connection. The motor control software is functional but various improvements were made to enhance its operation and to fix undocumented issues from the inherited project design. The inherited design receives 5-byte strings from the GUI application, which indicate axis, speed and direction. Each time a polling interrupt triggers, the controller checks the input buffer for a new command and when received, initializes a PWM signal on the microcontroller board output signals for the respective axis. Also included are an axis-enable and directional signal (forward, backward). The duty-cycle of the PWM signal indicates to the motor control subsystem's motor drive assembly the desired speed. The microcontroller code was modified to increase the smoothness of the stepper motor rotation and to reduce overheating. Additionally, the modified microcontroller enters a run loop which and accepts manipulator control in a "go" or "stop" form per axis. This method allows the PWM signal to operate without interruption with every received command.

The existing software subsystems from the previous design did not include support for remote control or any Internet-based interaction with the system. A software component has been developed to support the addition of the remote control and real-time visual feedback capabilities. The software GUI has been augmented to support this enhanced functionality. The software support for the network-based capability has been implemented using Java code. The Java components of the software subsystem are instantiated within the MATLAB-based GUI through the MATLAB Java Runtime Environment. This allows for a simple integration between the GUI and the network architecture, within minimal software deployment installation requirements. The network support provided is based upon the standard TCP/IPv4 protocol suite and UDP, allowing for connectivity over the public Internet. Controls are available to the user to allow for modification of the quality of the real-time visual feedback, allowing for a performance adjustment at run-time depending on actual overall network connection speeds. Compression is performed by the network software to improve performance and decrease required bandwidth. A visual refresh rate of 30 frames per second is desired, and the networking components seek to achieve this ideal rate with an image resolution of 720-by-480 pixels or greater.

Two standalone software GUI applications are provided and are required for use of the manipulator: the server and the client, separately. The server application is launched onto a computer connected to the nanomanipulator and to the microscope camera. The server program provides a basic GUI showing the status of the manipulator system and also Internet connection information. The client application provides a connection dialog into which the end-user enters the connection information provided by the server GUI. Upon successfully connecting the client application provides a real-time video feed from the microscope camera and input control is accepted.

The software GUI network components created with MATLAB and Java are built into distributable executables using the MATLAB compiler. The requirements to use the distributed server and client application executables are only the Microsoft Windows operating system and the royalty-free MATLAB Compiler Runtime.

RESULTS AND DISCUSSION

Testing will be implemented to confirm that all system specifications are evaluated, with the complete and final system. Final testing results are documented below. Range of motion was found by measuring the maximum travel distance of the piston at full stroke and dividing by 2 assuming starting from mid stroke. The range of travel was found to be 5 mm. The sampling rate has been tested between the test client and the host at RIT as well as other system locations. The specification for sampling rate is less than 60 Hz. Speed of travel has been tested by measuring the time taken to move a distance across the microscope stage from the time the system receives the start command from the user to the time the system receives the stop command, and determining the associated speed. The results are documented below in Table 1. With the current manipulator design the Y moves the entire system, the X axis moves the Z axis, and the Z axis moves the pipette. The Z axis currently uses a single acting cylinder which has a return spring that is stiffer than the team recommends. The team suggests replacing the Z axis cylinder with another double acting cylinder, modified by removing the large internal o-ring and plugging the external port, like the other cylinders. The speed results make sense based on the weight each axis carries and the impact of gravity and the return spring on Z. Speed would increase with decreased backlash and increased system stability.

<table>
<tr><th>Speed (um/s)</th><th>CQS Forward</th><th>CQS Reverse</th><th>Eppendorf Forward</th><th>Eppendorf Reverse</th></tr>
<tr><td>X Axis</td><td>0.0392</td><td>0.0240</td><td colspan="2" rowspan="3">2045</td></tr>
<tr><td>Y Axis</td><td>0.0150</td><td>0.0197</td></tr>
<tr><td>Z Axis</td><td>0.0060</td><td>0.0062</td></tr>
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Table 1: The above table shows the results of speed testing

System backlash has been measured by counting the number of revolutions required to start motion from a stationary position in both forward and reverse. Results are documented on the table below, and make sense taking into account the axes loads discussed previously. The system was run to both maximum and minimum stroke, using the CQS cylinders with no damage to the system or microscope. The CQS cylinders were found to not leak even at the systems highest pressure at maximum stroke.

Backlash Summary (rev)	CQS Forward	CQS Reverse	Eppendorf Forward	Eppendorf Reverse
X Axis	0.50	0.75	Negligible Backlash	
Y Axis	3.38	3.58		
Z Axis	2.92	2.50		

Table 2: The above table shows the system testing results for backlash

Resolution has been tested by measuring the distance traveled by the nanomanipulator, when motion is stopped as soon as visible motion occurs. The test was run at the lowest motor speed at a magnification of 50x. The system was shown to fail to meet the specification of 100 nm of resolution or less, however in benchmark testing the Eppendorf manipulator was found to only have a resolution of 500 nm using the above mentioned testing method. Figure 6 below shows the movement of the pipette during resolution testing. Testing is documented in the table below.

	CQS	Eppendorf
	Resolution (nm)	Resolution (nm)
X	1601	500
Y	4325	

Table 3: The above table shows system testing results for resolution

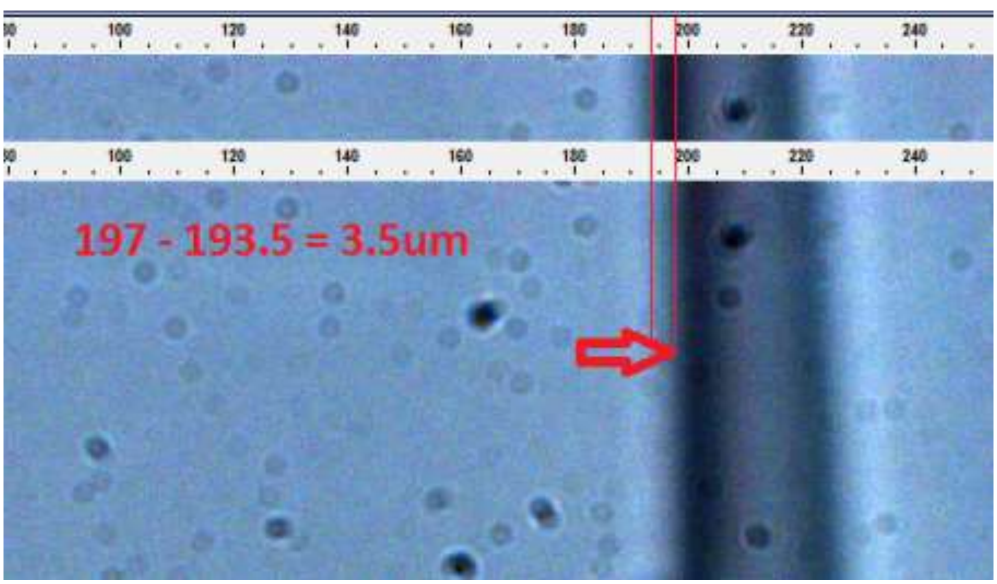

Figure 6: The above figure shows the pipette position before (above) and after (below) resolution testing. Motion can be observed with reference to the point change in position of the red line.

As noted in the table below the project went $90 over the extended budget of $1,352. The budget was initially extended to $1,352 from $1,000 to allow for the purchase of spare cylinders. The project went over budget due to the unexpected expense of replacing the mounting device used by previous teams which was relocated to a different section of the lab, this expense totaled $42.20. Added expenses were also incurred with the purchase of the new CQS cylinders and o-rings to attempt to modify the leaking MQP cylinders. All purchases were approved by the team's guide and customer. The final system is over $75 under budget to reproduce for potential widespread use.

For widespread use the team recommends examining the possibility of producing the manipulator mounting brackets from sheet metal to reduce weight and cost.

#	Specification (metric)	Unit of Measure	Target Value	Theoretical Value	Actual Value	Previous System
S1	Size of manipulator (h x w x l)	cm	8 x 8 x 8	13 x 12 x 12	13 x 12 x 12	13 x 13 x 13
S2	Weight of manipulator	Grams	550	400	400	689
S3	Development cost	$	1,352	1,441.81	1,441.81	2,128
S4	Cost to manufacture after development	$	1000 - 1500	1,413.01	1,413.01	1,470
S5	Limits of travel in each direction	cm	>0.25	0.5	0.5	1.1
S6	Speed of travel	mm/sec	0.5	.088	0.0392	0.04
S7	Observed Resolution	nm	< 100	86.74	1601	Eppendorf 500
	Theory Resolution (From Speed)	nm	<100	86.74	14	56
S8	Sampling Rate	Hz	60	0	60	NA
S9	Level of Difficulty of Use	Binary	Easy	Easy	Easy	Medium
S10	Supported Control Software	Binary	Yes	Yes	Yes	Yes
S11	Visual Feed Sampling Rate	Hz	60	60	60	NA
S12	System is Controlled by a Device (Remotely and Locally)	Binary	Yes	Yes	Yes	Locally
S13	System Provides Additional Feedback	Subjective	Yes	Yes	Yes	No
S14	System Provides Calibration	Binary	Yes	Yes	Yes	No
S15	System Backlash	Revolutions	<3	0	2.27	25
S16	Video Latency	Frames Per Second	>30	30	30	NA
S17	Control Latency	ms	<200	200	~100	NA

Table 4: The above figure continues to show customer specifications

CONCLUSIONS AND RECOMMENDATIONS

Overall this project was a success. The team was able to deliver a system with improved speed, decreased backlash, and remote access capabilities. While the achieved speed was below specifications, it is twice the speed of the previous iterations if backlash is discounted at 0.072 mm/s, and allows the microscope stage to be traversed within 21 seconds at maximum speed in the lowest magnification of 10x. The system backlash was reduced from 25 revolutions to below the specification of 3 revolutions or less. The filling method was greatly simplified and the new system does not leak or require refilling, which is a great improvement over the previous iteration that allowed air to enter the system if left overnight, and took approximately an hour to refill. Remote access is now available, and the manipulator GUI now includes video feedback to improve resolution. Improvements could still be made to the system to account for some system drift and the speed could be further improved. Improvements could also be made to the unit's mounting device. The current system uses a magnetic stand and a rubber coated beaker grip to hold the manipulator. This device is effective and is somewhat adjustable, however something more stable and with improved aesthetics should be considered. The use of ball bearing tracks instead of the current tracks in the manipulator sub-system could improve system stability. The team learned valuable lessons about supplier management and the need to ask very specific questions about products. It is also best to speak to engineers at the company rather than suppliers, although they may be more difficult to contact. The team's difficulties with suppliers and components also pointed out the advantage of always having a plan b and showed how critical a thorough plan for risk management is. Despite difficulties with suppliers the team was able to provide significant improvement to the system. This project has been accepted for the American Society for Engineering Education's Conference. Overall the customer seemed satisfied with this iterations progress, particularly improvements in system backlash and the addition of remote capabilities.

REFERENCES

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[2] Bastardi, J., Hughes, R., Loebner, S., Ling, B., Olan, B.. "*P12371: Nanomanipulator*". Rochester, NY: Rochester Institute of Technology. Web. 23 Nov 2013.

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ACKNOWLEDGMENTS

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