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HYDRAULIC NANOMANIPULATOR FOR THE ADVANCEMENT OF NANOSCIENCE

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ABSTRACT

A nanomanipulator is an ultra-high precision positioning instrument used in biological applications. A typical commercial hydraulic nanomanipulator can cost well over $10,000 and is controlled manually. The main objective of team P13371 was to broaden participation and collaboration in nanoscale science in secondary education by creating an economical and functional hydraulic nanomanipulator. This was realized by adding computer controls and lowering the cost of manufacturing to below $1500. An additional goal was to position a pipette under a microscope in order to conduct experiments. This project is in its second phase, following the work done by group P12371 or phase one; therefore, a final goal of the team was to improve on the design implemented previously. The design obtained a resolution of 56 nm of movement at a manufacturing cost of $1471. The biggest shortcoming of the design was a system backlash of 3 revolutions. While this was a significant improvement from the 14 revolutions achieved by phase one, it did not meet the team defined specification of less than 1 revolution.

INTRODUCTION

The goal of the project was to broaden participation and collaboration in nanoscale science by creating a cost-effective and operative nanomanipulator that enables a person to perform nanoscale manipulations. The manipulator implemented should be electronically actuated, controlled by a joystick or computer interface, obtain a resolution of 100 nm/step, and have three axes of movement. The instrument is used to position a pipette and potentially other similar objects underneath a microscope in order to conduct experiments such as cell manipulation or mechanical/electrical testing on nanotubes.

The project aims to develop a controllable nanomanipulator that achieves competitive operational specifications while being a significantly cheaper alternative to currently available solutions. This project is the second phase of the project building upon the work done in project P12371[1].

PROCESS

A list of customer needs and specifications were provided to the team through the PRP document. The needs and specifications were prioritized and revised after discussions with the customer and are shown below in Tables 01 and 02.

Table 01: Customer Needs

Customer Needs		
#	**Description**	**Rank**
CN1	Resolution	9
CN2	Low Cost	9
CN3	Reliable Movement	9
CN4	Easy to Operate	9
CN5	Visual Feedback	3
CN6	Adequate Range of Motion	3
CN7	Reliable Control of Speed	3
CN8	Keep Hardware Safe	3
CN9	Easy to Maintain	1
CN10	Easy to Setup	1
CN11	Portable	1
CN12	Remote Access	1

Table 02: Specifications

#	Specification (metric)	Unit of Measure	Target Value
S1	Size of manipulator (h x w x l)	cm	8 x 8 x 8
S2	Weight of manipulator	Grams (oz)	550 (20)
S3	Development cost	$	< 2,500
S4	Cost to manufacture after development	$	< 1000
S5	Limits of travel in each direction	cm	1
S6	Speed of travel	m/sec	TBD
S7	Resolution	µm	< 0.1
S8	System backlash	µm	< 1
S9	System drift	µm/min	< .02
S10	System is easily assembled/disassembled	Survey	Yes
S11	Ease of use	Survey	Yes
S12	Joystick Control	Binary	Yes
S13	Safe full range of motion	Binary	Yes
S14	System mounts standard pipette holder	Binary	Yes
S15	GUI Control	Survey	Yes
S16	Remote internet access	Binary	Yes

To prioritize the specifications, a House of Quality was created and can be seen in Fig. 01. From the chart; the resolution, position repeatability and the manufacturing costs were the highest priority specifications.

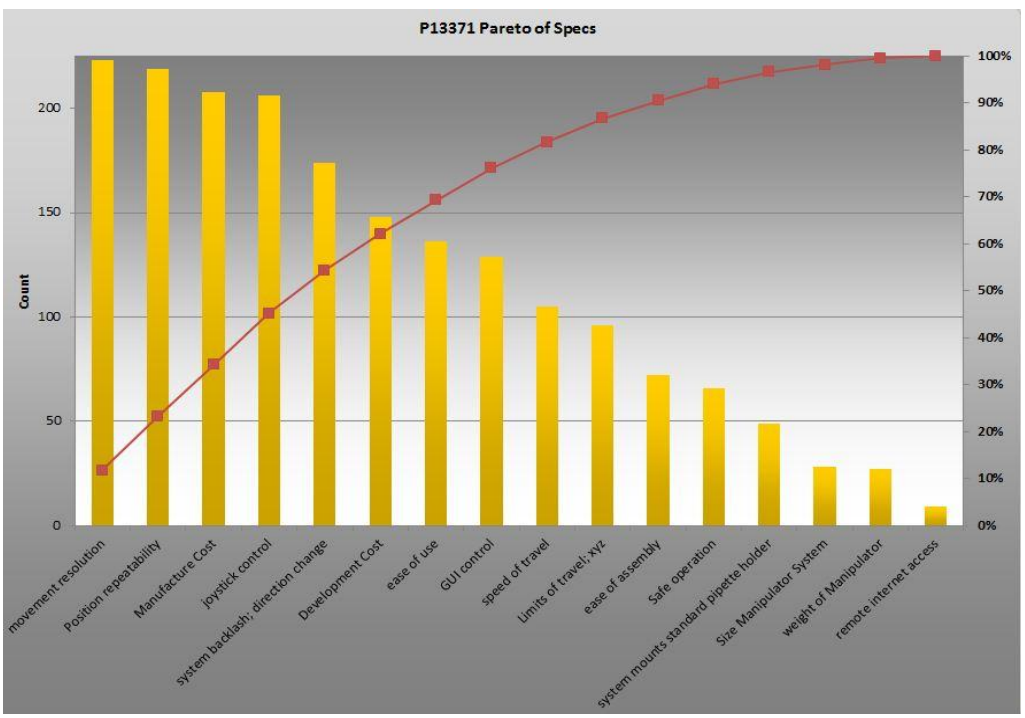

Figure 01: Pareto of Customer Specs

System Selection

Phase one developed a hydraulic nanomanipulator that was able to achieve 53nm of resolution at a cost of $1650. The manipulator was controlled either via a joystick or computer GUI. While the project managed to meet some of the customer specification, there were some issues such as unreliable controls, backlash and position repeatability. The goal of the second phase of the project was to modify the existing design, to eradicate those issues and reduce the manufacturing costs of the system.

Since phase one was successful in achieving the resolution specification, the overall design concept was retained and can be seen in Fig. 02. The design consists of three stepper motors that individually drive a lead screw assembly. The lead screw actuates the piston cylinder which is connected to corresponding piston cylinders on the manipulator via hydraulics. The cylinders on the manipulator are placed on linear slides that move the x, y and z axes. The stepper motor receives signals from the control board that is connected to a computer. Signals can be sent to the board using a joystick or a GUI.

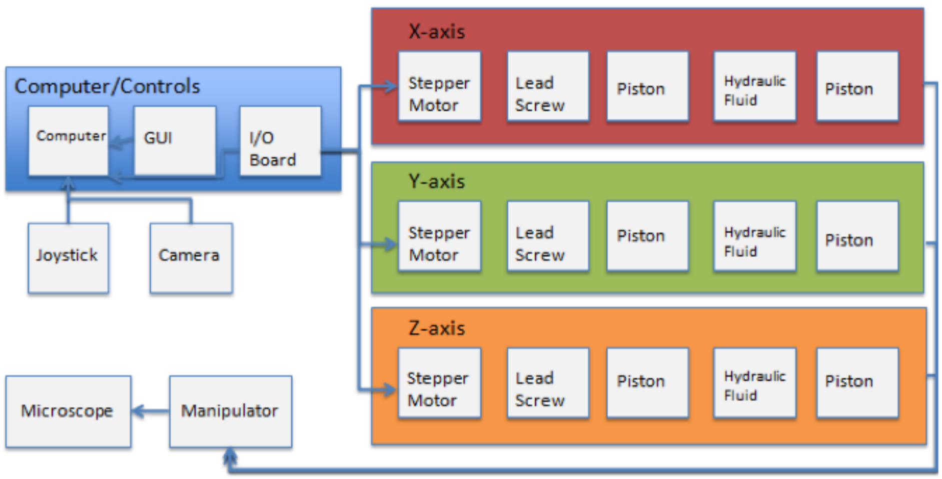

Figure 02: System Architecture

Pump Subsystem

Phase one used stepper motors that were capable of micro-stepping in order to achieve the required resolution of less than 100nm. One of the biggest drawbacks of micro-stepping is that when the micro-step is increased, the motor torque decreases exponentially [2]. The phase one design intended to use 64 micro-steps per full step of a typical stepper motor which would cause a 97% torque loss.

The micro-stepping motors were replaced with stepper motors with planetary gears. The planetary gears remove the necessity of micro-stepping while maintaining much higher torques with a small increase in cost. The calculation for the resolution can be seen in Eq. 1. The lead screw utilized had a lead 0.3175 mm/rev. The nut on the lead screw was attached to the piston of a cylinder that was hydraulically connected to a cylinder on the manipulator subsystem. The bore diameters for the cylinders were 3/8" and 1/2" respectively leading to a hydraulic advantage of 1.78.

$$Resolution = Lead * \frac{Step\ Angle}{Gear\ Ratio} * Hydraulic\ Ratio \tag{1}$$

$$Resolution = 0.3175\frac{mm}{rev} * \frac{1.8°}{step} * \frac{1}{13.76} * 1.78 = 65nm$$

Use of the planetary gears meant that the speed of travel specification would not be met as shown in Eq. 2. However; as displayed Fig. 01, the speed of travel is not a high priority and the customer deemed the design speed acceptable. The final design of the pump assembly can be seen in Fig. 03.

$$Speed = RPM * Lead * \frac{1}{Hydraulic\ Ratio}$$
$$Speed = 22\frac{rev}{minute} * 0.3175\frac{mm}{rev} * \frac{1}{60}\frac{minute}{second} * \frac{1}{1.78} = 0.104mm/s \qquad (2)$$

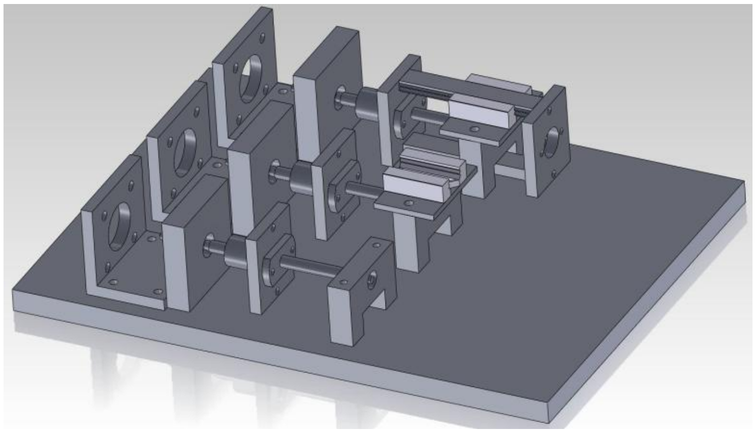

Figure 03: Pump Subsystem

Hydraulics Subsystem

One of the biggest complications for phase one was the backlash in the system. The backlash was approximately 14 revolutions of the motor in order to change direction. A major cause of this was air in the hydraulic lines. Columns of air were clearly visible in the hydraulic lines due to improper sealing and bleeding. Air has a bulk modulus of 0.142MPa compared to bulk modulus of water at 2,150MPa. It is easier to compress air rather than water by several orders of magnitude. The calculation shown in Eq. 3[3] determines the backlash caused by a 5mm column of air in a 5mm diameter pipe when a pressure of 294kPa is applied.

$$dV = \frac{P * V}{Bulk\ Modulus\ of\ Air} = \frac{2.94e05\ Pa * (\pi * 0.005^2 * 0.005)m^3}{0.142\ MPa} = 1.07 * 10^{-9}m^3 \qquad (3)$$

In order to reduce the backlash caused due to air in the hydraulic lines, the clamped, barb fittings of phase one were replaced by double compression fittings. The double compression fittings provide better sealing and allow easier bleeding of air. Figure 04 shows the hydraulic system design.

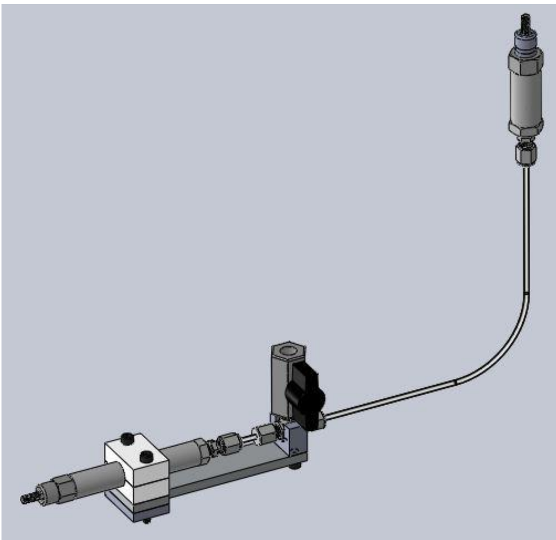

Figure 04: Hydraulic Subsystem

Manipulator Subsystem

The previous design utilized a friction slider that would be moved by a hydraulic cylinder. Three of these systems were created and attached together in an x-y-z fashion. While the design was sound, the implementation of the system was executed inadequately; misalignment and high friction sliders caused the output force required to move the sliders to increase.

To combat the high friction, the friction sliders utilized in phase one were replaced with smaller sleeve bearing-style sliders. These sliders have an approximate coefficient of friction of 0.547, compared to the plain friction slider that had a coefficient of friction equal to 1.0. This reduced the required force on the manipulator by 45.3%. Another factor affecting friction was the weight of the system. The sleeve bearing sliders helped reduce the weight of the system from 750g to 689g resulting in the force required by the hydraulic system to be reduced down to 0.83N from 3.25N. Figure 5 shows the forces acting on the carriage and the resulting calculations are shown in Eq. 4 through 7.

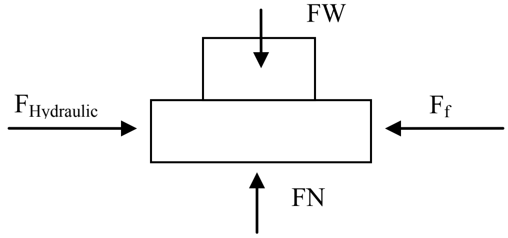

Figure 05: Stack Up of Three Axis and Forces Experienced by Carriage

$$\sum Fy = ma = 0 \tag{4}$$

$$FN - FW = 0 \tag{5}$$

$$FN = FW = 153.68g(9.81\frac{m}{s^2}) = 1.51N \tag{6}$$

$$Ff = \mu FN$$

$$Ff = (.547)(1.51N) = 0.83N \tag{7}$$

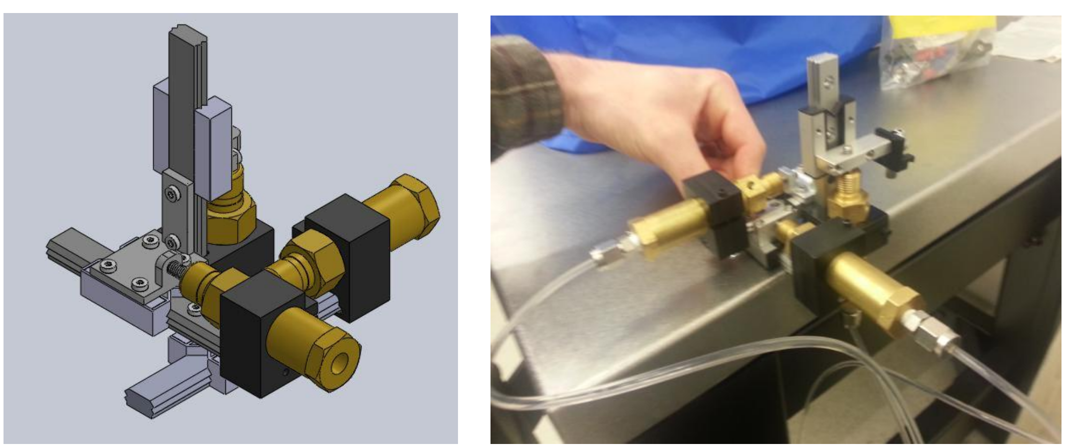

Figure 06: Manipulator Assembly in CAD and Hardware

Controls Subsystem

The controls systems starts with the graphical user interface (GUI). This was adopted from the work done by phase one with a few minor improvements. The GUI was developed in java using eclipse development software. The changes made to the GUI include the addition of a point grey microscope camera live feed embedded in the GUI. At the time of publication, the point grey camera live feed was non-functional but further work will be done in the near future. The step values in the speed setting were also adjusted to more accurately represent the system as built. The GUI outputs control signals via a serial cable. The control signals are structured as, axis (1 bit) speed (3-bits) direction (1-bit) (i.e. "x1110" would be a step on the x-axis at speed 8 in the CCW direction). Control signals can either be generated via a USB joystick or control buttons right on the GUI.

The serial cable is connected to a freescale microcontroller. This microcontroller was used previously by phase one and was donated for prototyping by the computer science department at RIT. The microcontroller code developed in C utilizes the on board pulse-width modulation (PWM) module to create the desired signals for the stepper motors. The enable and direction pins are set by manipulating output PORTA [4]. The pin-out can be seen in fig. 08. The program works by waiting and accepting a signal from the GUI and jumping to the setpins( ) subroutine. In this routine, the direction, speed and axis are determined; the direction pin is set; the PWM is set and enabled depending on the axis control signal received. The reset timer is also set in this routine. This timer is programmed so that at the slowest speed, only one step will be transmitted. At a higher speed setting, more steps are allowed before disabling the PWM. This allows the user to single step a desired axis when operating at the slowest speed. A timing diagram is shown in Fig. 07 for the different PWM speed settings and the reset signal. The reset signal is shown in yellow while the stepper motor pulses are shown in blue.

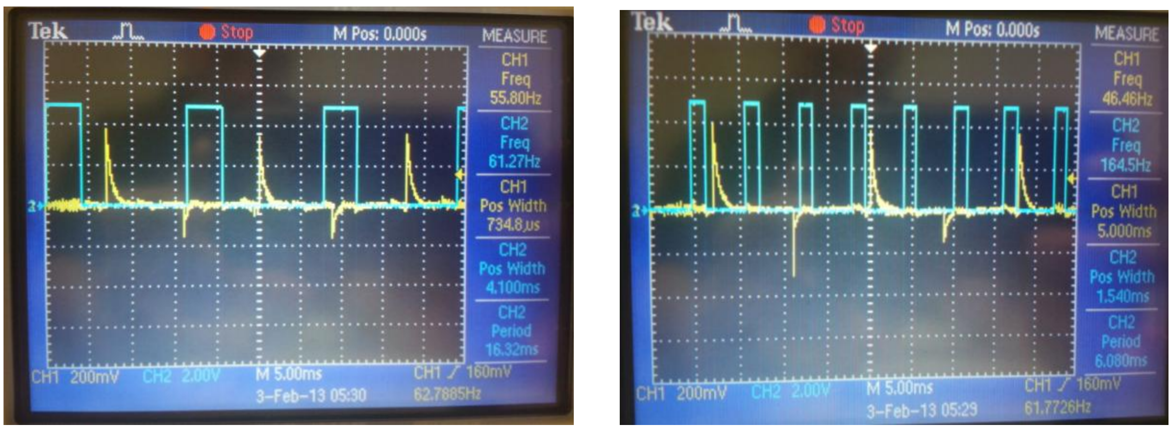

Figure 07: Control Signals – Single Step Mode Speed 1(Left); Speed 4 (Right)

The signals are sent to the motor control board via a custom made cable and the connection can be seen in fig. 08. The motor control board is able to control three independent stepper motors and utilizes the TB6560 H–bridge motor driver chips. A pre-made board was purchased after phase one attempted to create their own. This cut down on debugging cost of replacement components and manufacturing time and was effective in the design.

				X-STEP	Y-STEP									Z-ENABLE	Y-ENABLE	X-ENABLE	Z-DIRECT	Y-DIRECT	X-DIRECT										
1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59
2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60
																Z-STEP													

Figure 08: Microntroller to Motor Control Board Control Signals Connection

RESULTS AND DISCUSSION

The subcomponents of the nanomanipulator were tested first before the entire system in order to pinpoint areas of improvement. From a mechanical stand point, the biggest issues were the backlash, lag and drift. Backlash was defined as the number of rotations required to change direction. Phase one's design had a system backlash of approximately 14 revolutions. When each individual axis of the current system was tested prior to manipulator assembly, the backlash was measured to be consistently under 0.5 revolutions for the x and y axes. The z axis however had a backlash close to around 2 revolutions. The z-axis had a cylinder on the pump assembly with a slightly longer stroke of 3.5" as opposed to 3" on the x and y axes. The longer stroke means more volume of water needs to be displaced in the cylinder. This could lead to the higher backlash. A shorter stroke cylinder was ordered to test this hypothesis. With the overall system assembled, the backlash increased from 0.5 revolutions to 3 revolutions. This is caused by the increased frictional forces when the whole system is assembled together. There are several methods to cut down on the backlash caused by the high friction. The first one is to use smaller, lighter cylinders to reduce the weight of the manipulator. The second option is to use sliders with roller or ball bearings to decrease the static friction.

The system backlash of 3 revolutions does not meet the required specification of less than 1 revolution; however, this result is a significant improvement from the 14 revolutions achieved by phase one's design. The improvement was due to two design modifications. The double compression fittings were successful in keeping air out of the hydraulic lines reducing the compression in the system, and the smaller pipe diameter resulted in a smaller volume of water to be compressed leading to a more efficient hydraulic system.

The second problem encountered in implementation of the design was the amount of lag present. The speed of the manipulator is not constant; therefore, there is a long period where the manipulator moves very slowly. Then as the pressure increases, it accelerates to its required speed. This is caused by the friction in the cylinders. The cylinders on the manipulator side contain two O-rings each and the cylinders on the pump assembly contain one O-ring each. Since the hydraulics system is a very low pressure system, it is difficult to overcome the static friction in the cylinders. As the hydraulics are compressed, the manipulator moves slowly, but then as the pressure in the hydraulics increases due to the compression, the static friction in the O-rings are overcome and the manipulator accelerates. This makes the motion unpredictable and difficult to control. The best solution to this problem is to use smaller cylinders with diaphragm actuation rather than cylinders with O-rings. Smaller cylinders will mean less volume of water, lighter weight on the manipulator side and the diaphragm actuators will allow for lower friction. This would result in less system backlash; a smaller, lighter manipulator and reduced lag leading to more efficient and reliable manipulator motion.

The resolution of each individual axis was also tested before and after the manipulator was assembled. There was no noticeable difference in resolution between the two tests. The x-axis had a resolution of 56 nm per every step of the motor. The y and z axes had a resolution of 51 nm/step and 56 nm/step respectively. The standard deviation of the resolution was ± 5nm.

A problem with phase 1—and a problem mentioned above—is the high friction on the manipulator side. With the high friction, a greater force is required to get the manipulator to begin moving. With the phase two using sleeve bearing sliders, as opposed to the pure friction sliders, the coefficient of friction was greatly reduced; going from approximately a coefficient of friction of 1.0 to a coefficient of friction of 0.543; a reduction of 45.3%. By reducing the weight of the system and the lower coefficient of friction from new sliders, the required force to overcome friction was reduced by 74%.

A major challenge of the project was to get the system to work reliably within the customer specs while still maintaining a price that is feasible to perspective clients that do not have $10,000 to spend on a commercially available nanomanipulator. The manipulator was given a $2,500 budget during the development stage with a goal of having the final manufacturing price of under $1,500. For the system proposed, the entire system can be built for approximately $1,471. While this number is very close to the $1,500 limit, it is within spec. Utilizing most of the development budget, $2,200 of $2,500, the overall final cost of the system was reduced by approximately $180 when compared to phase one.

The controls subsystem was improved upon by increasing the functionality and robustness of the design. Much of this was achieved through the purchase of a commercial available controls board. An h-bridge stepper motor control circuit is a complicated system and the board makes it easy to implement while utilizing the TB-6560 motor drive chip. Though the inputs to this board are not isolated per the manufactures claims, that is the only issue that was encountered. By improving the controls and creating a robust system, the systems position repeatability is greatly improved and is able to drive the entire three axis system effectively and efficiently.

CONCLUSIONS AND RECOMMENDATIONS

The majority of the customer needs were met. A weighted priority was assigned to each customer specification while conducting the house of quality analysis. The results after completing all tests showed that 83% of the customer needs were met. A resolution of 56 nm/step with a deviation of ± 5nm was achieved. The design maintained the resolution of phase one while significantly improving the consistency of the manipulator's movement. The overall manufacturing cost of the system was reduced $180 down a total of $1471. The robustness and reliability of the controls were also vastly improved with the help of a commercially available control board as opposed to developing one.

A major factor in achieving the required specifications was the quality of manufacturing. Since the hydraulic nanomanipulator is a high precision instrument, the tolerances on the machined parts can have a large impact on the accuracy of the system. To achieve the required level of consistency and precision, a large amount of time was allotted for machining the mechanical parts. A lot of effort was also put into ensuring all the air in the hydraulic lines was bled. This was one of the major factors which helped in the reduction of backlash.

The main specification that was not met was the backlash of the system. While the specification for backlash was not met, a significant improvement from phase one was achieved. The backlash was reduced to less than 3 revolutions from 14 revolutions. Backlash of around 0.5 revolutions was recorded when the individual axes were tested without the manipulator assembled. The increase in backlash after the assembly of the manipulator is probably due to the increased friction. When the manipulator is assembled, the weight of the cylinders increases the normal force acting on the slides. Smaller and lighter cylinders will help to reduce the friction and the backlash in the system. Another factor that could help reduce the backlash is using cylinders with diaphragm actuators instead of cylinders with O-rings. The diaphragm actuators reduce the friction inside the cylinder, making the change in direction less challenging.

The size and weight of the manipulator could also be reduced using smaller cylinders. The size and weight specs were not met; however, they were not high priorities and approval of the design was obtained from the customer.

Future work on the hydraulic manipulator design would be to improve on the backlash reduction and the quality of movement. One of the ways to achieve this, as mentioned earlier, would be to use smaller cylinders with diaphragm actuators. Reducing the overall length of hydraulic lines would also reduce the volume of water resulting in lower compression in the hydraulic system. The friction in the manipulator can be reduced with the use of sliders that contain bearings to allow for smoother movement. A computer engineer for future work would also be highly recommended in order to replace the serial cable to a USB in order to communicate with the control board, and to help develop a program for remote accessing the manipulator over the internet.

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