Multidisciplinary Senior Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: P12371

DEVELOPING A NANOMANIPULATOR TO BROADEN GLOBAL PARTICIPATION IN NANOSCIENCE

Jaclyn Bastardi
Mechanical Engineering

Robert Hughes
Mechanical Engineering

Sabine Loebner
Computer Engineering

Bradley Ling
Mechanical Engineering

Bradley Olan
Mechanical Engineering

ABSTRACT

The primary objectives of P12371 were to develop a computer controlled nanomanipulator that was of lower cost than those currently found on the market. A nanomanipulator is an ultra high precision instrument used in single cell manipulation, injection, and aspiration. It reduces human hand movements to increments as small as 100 nanometers. The task of this project was to design a new low cost mechanical manipulator, and to control this manipulator with a PC based user interface that mimics performance characteristics of commercially available manipulators.

INTRODUCTION

Current manipulators are expensive, ranging from $7,000 to $50,000, and require years of experience to setup and operate in conjunction with a microscope. The two main objectives of the project were to design and build a low cost, portable, high precision hydraulic manipulator that can be electrically actuated and to develop a computer-based workstation complete with joystick control and visual feedback. The manipulator should be able to obtain a resolution of 100 nanometers, have three axis movement, and be operated either through a user interface or joystick.

If these objectives are met, it will broaden participation in nanoscience on a global scale. Scientists in locations all over the world who do not have access to nanomanipulators would be able to remotely control one in a lab that has access to them. Accessibility will also be increased by reducing the cost of the entire system to less than $2,500.

DESIGN PROCESS

Customer Needs and Specifications

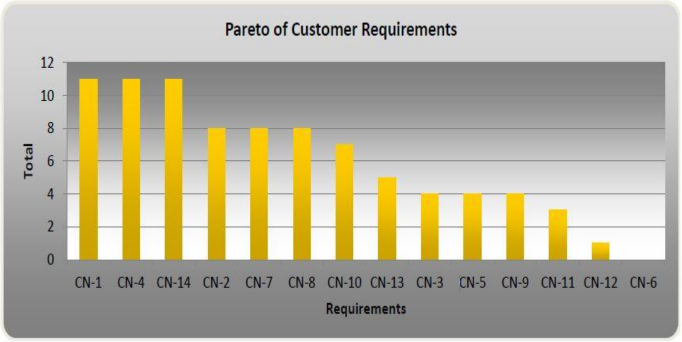
From the information given in the projects PRP, it was felt that the best approach was to go through customer needs and specifications to rank them in order of importance. Various ideas were brainstormed and researched, and after each one was critically analyzed to see how well they suited the needs of the project. Using this method it was possible to narrow down the best options and easily choose which option was best for the project as a whole.

One of the first tasks was to determine the importance rating for each customer need. These were ranked by comparing each need to every other need to determine which was more important. Then the total score for each need was ranked to determine the most important. The customer needs can be seen in Table 1, and the final Pareto comparison of the customer needs can be seen in Figure 1.

Table 1: Customer Needs

CN-1	Manipulator will have fluid based 3-axis motion
CN-2	System Controllable via a computer
CN-3	System mounted independently of microscope stage
CN-4	System able to mount standard pipette holder
CN-5	Manipulator mimics performance of other commercially available manipulators
CN-6	System Actuators are of the same design and dimension
CN-7	System is designed to be low cost
CN-8	Electrical control is performed through a computer stationed at the optical microscope
CN-9	The control software is standard issue at RIT or well supported free-ware (avoids costly software)
CN-10	Live camera feed from microscope provides visual feedback
CN-11	Manipulator will have adjustable speed settings
CN-12	System has an intuitive interface located at microscope computer
CN-13	Control software and algorithms are contained on a computer stationed at the optical
CN-14	System is controllable with and without a joystick

Figure 1: Pareto Comparison of Customer Needs

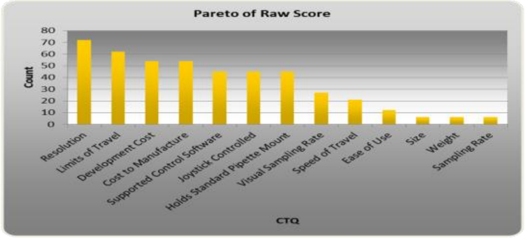


From this comparison method it was found that the most important customer needs were that the manipulator has fluid based 3-axis motion, that the system is able to mount a standard pipette holder, and that the system is controllable with and without a joystick. The other customer needs that will be focused on are that the system was controllable via a computer, that the system was designed to be low cost, and the electrical control is performed through a computer stationed at the optical microscope.

Table 2: Customer Specifications

	Function	Specifications	Unit of Measure	Marginal Value	Ideal Value
S1	Manipulator	Size(h x w x l)	cm		8 x 8 x 8
S2	Manipulator	Manipulator Weight	grams		550
S3	System	Development Cost	$	1000	<2500
S4	Manipulator	Manufacturing Cost	$	250	<500
S5	Manipulator	Limits of Travel	cm	0.25	1
S6	Manipulator	Speed of Travel	m/sec	TBD	TBD
S7	Manipulator	Resolution	μm	5	<1
S8	Interface	Sampling Rate	Hz		60
S9	Interface	Ease of Use	Binary		Yes
S10	Interface	Supported control software	Binary		Yes
S11	Interface	Visual Feed Sampling Rate	Hz		60
S12	Interface	Joystick Controlled	Binary		Yes
S13	Manipulator	Standard Pipette Holder	Binary		Yes
S14	Manipulator	3-axis motion	Binary		yes

Figure 2: Pareto Comparison of Specifications



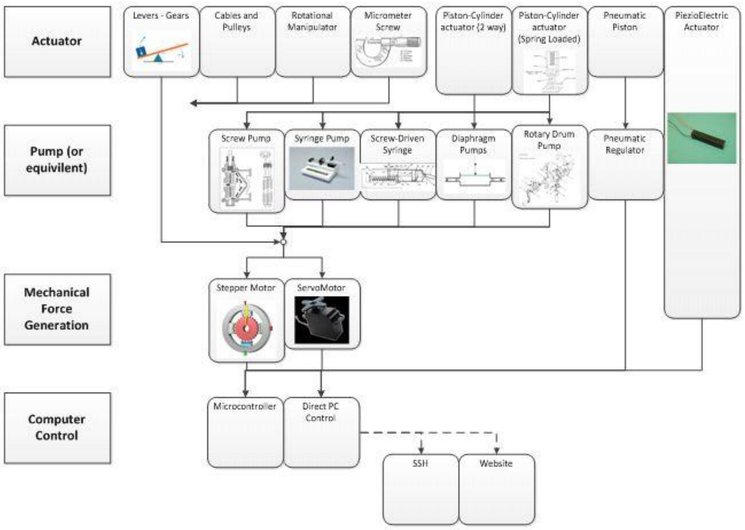
A House of Quality Matrix and Pareto comparison was used to set the order of importance of the customer specifications. The specifications can be seen in Table 2, and Figure 2 shows the Pareto of specifications. From this comparison method the top specifications were resolution, limits of travel, development costs, and cost to manufacture. The house of quality analysis maps the specifications to the needs to ensure that all of the needs are represented by a specification.

System Selection

After brainstorming and research into possible solutions for this project, it was decided that the best way to approach system selection would be to split the nanomanipulator into four subsystems: the actuator subsystem, the pump subsystem, the force generation subsystem, and the computer control subsystem. A morph chart, shown in Figure 3, was created to show all the possible combinations of the individual subsystem concepts.

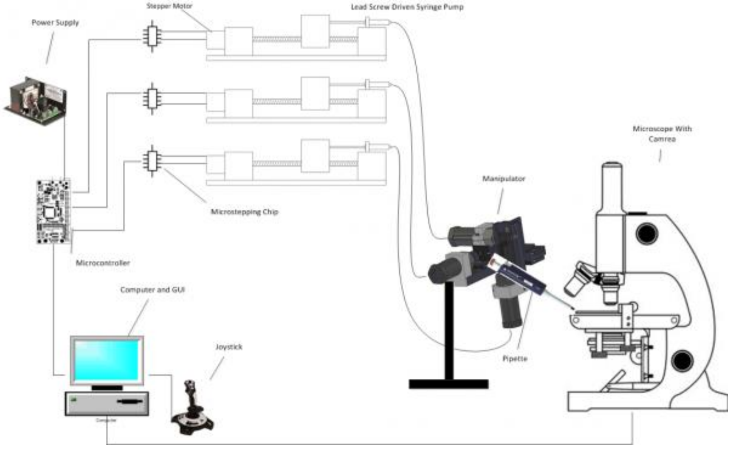
Research was done into each of the possible solutions individually. Using a comparison matrix each individual solution in the subsystems were compared based on how well they met important specifications. Each specification was given a certain weight, while the solution was rated on a scale from -3 to 3, not meeting specifications to completely meeting specifications respectively. The raw score was calculated and the choices with the highest raw scores were further discussed and evaluated.

Figure3: Morph Chart



The final design consists of a joystick sending signals to a computer that will output to a microcontroller. The microcontroller translates these signals to a stepper motor that will turn a lead screw assembly that will move a piston cylinder arrangement. These piston cylinders will drive corresponding piston cylinders at the actual manipulator and actuate linear sliders to moves three axis. The pipette will be mounted to the vertical axis. The system architecture is shown in Figure 4.

Figure 4: System Schematic

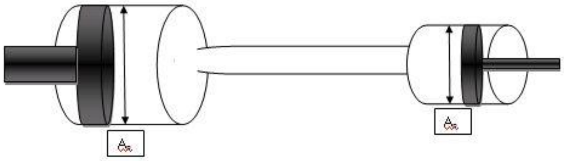


Piston and Cylinder Selection

When planning the hydraulic system it was decided that the most realistic approach to connecting the actuator subsystem to the lead screw and pump subsystem was via piston and cylinder assemblies. Through a hydraulic system the required resolution and range of motion could be achieved. When looking into purchasing the piston and cylinder assembly numerous aspects were taken into consideration. For the actuator piston and cylinder a large diameter was needed without the assembly itself getting too large. The piston and cylinders could be purchased with different stroke length, or the distance the cylinder could be moved. To have the full range of motion on the actuator subsystem it was decided that a ½" (12.7mm) stroke was desirable. After researching different options the RC-500 Series model from Cylinder & Valves, Inc. was chosen. This piston and cylinder had an inner diameter of ½" (12.7mm), a stroke of ½" (12.7mm), and a U-cup seal to allow for small movement. A spring was added into the piston and cylinder to allow for returning motion.

For the pump assembly a piston cylinder with a smaller diameter and larger stroke was needed. From Cylinders & Valves, Inc. the RC-300 Series model was also purchased. It features an inner diameter of 3/8" (4.191mm), a stroke of 3" (76.2mm), and also a U-cup seal. Using the area ratios, equation 1, the overall range of motion for the hydraulic system can be shown using the calculation below. The overall range of motion on the actuator subsystem will be 42.86 mm.

Figure 5: Hydraulic System Diagram



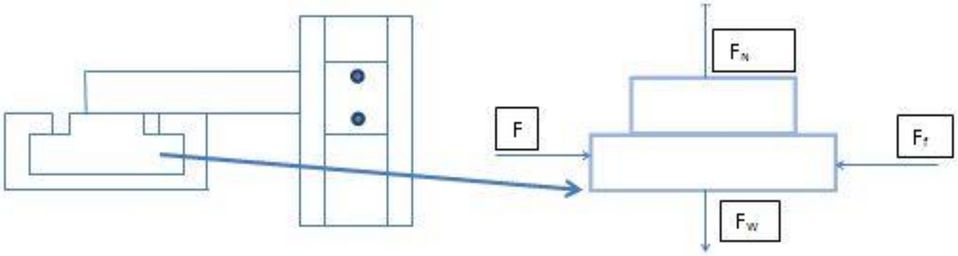
$$r_a = radius\ of\ actuator\ piston\ \&\ cylinder = .125\ in = 3.175mm$$
$$A_a = area\ of\ actuator\ piston\ \&\ cylinder = .196\ in^2 = 126.676\ mm^2$$
$$r_p = radius\ of\ pump\ piston\ \&\ cylinder = .1875\ in = 4.7625\ mm$$
$$A_p = area\ of\ pump\ piston\ \&\ cylinder = .1104\ in^2 = 71.256\ mm^2$$

$$v_p A_p = v_a A_a \quad \rightarrow \quad \Delta x_a = \Delta x_p \frac{A_p}{A_a} \qquad (1)$$
$$if\ x_p = 76.2\ mm$$
$$then\ x_a = 42.86\ mm$$

Actuator Subsystem Design

The first step in designing the manipulator was to determine how motion would be achieved in three axes. After much research into current manipulator design and liner motion products, simple carriages into rail sliders were selected. The specifications for the sliders met size, moment, force, and friction requirements. The force required to move the X-axis was determined as this would be the axis with the most weight on it as shown in Fig. 6, thus being the max force needed to be supplied by the piston and cylinder. The calculation is shown below.

Figure 6: Stack up of three axis and forces experience by carriage



Weight of Y-axis and Z-axis sliders: 60 grams
Motor Weight: 136 grams
Total Weight: 332 grams

$\Sigma Fy = ma = 0$ (2) $FN - FW = 0$ (3) $FN = FW = 332g\left(9.8\frac{m}{s^2}\right) = 3.25N$ (4)

$Ff = \mu FN$ (5) Max load factor at low speed applications is <u>1.0</u>

$Ff = (1.0)(3.25N) = 3.25N$ (6)

$\Sigma Fx = ma = 0$ (7) $F - Ff = 0$ (8) $F = Ff$ (9) $\underline{F = 3.25N}$ (10)

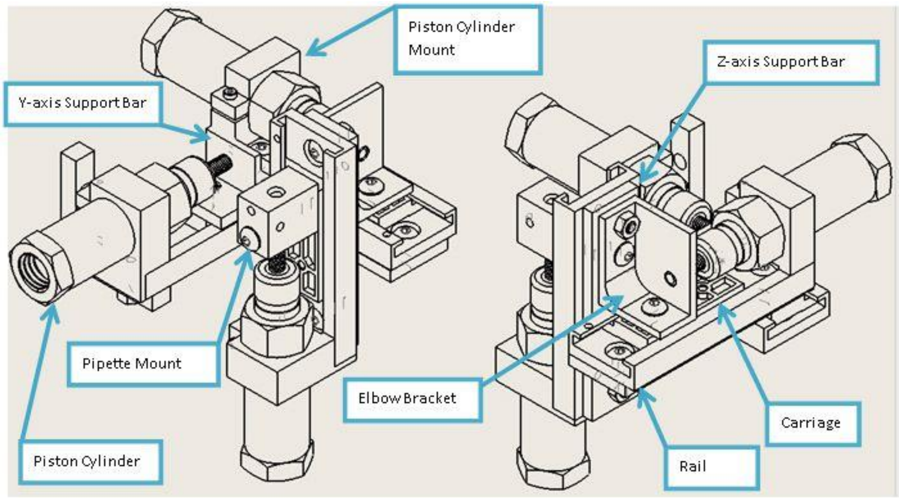
Thus, the force needed to be generated by the piston cylinder is 3.25N, well within the capabilities of the system.

The next design challenge was mounting the piston cylinders to the rails. Small mounting blocks were used that had holes to accommodate the diameter of the cylinders. A slot was cut into the blocks that would allow the blocks to act as a clamp once screwed into the rails. A back tab was used on the X and Z-axis to prevent the mounts from experiencing torque.

Once the X-axis had a piston cylinder mounted to it, a mechanism was designed so that could mount the Y-axis to it while eliminating torque on the Y-axis. An "L" shaped spacer block was used that would screw into the two holes of the X-axis carriage, extend off to the side of the axis, and have two screw holes that would allow the Y-axis rail to be mounted to it. A tab was left up to allow the X-axis piston cylinder to thread into which would allow retraction of the sliders. This tab also prevented the Y-axis piston and cylinder mount from experiencing torque.

After the Y-axis was securely mounted, the Z-axis mounting remained. To achieve this, an elbow bracket was machined that would allow the Z-axis to hang off the side of the Y-axis. The bracket would be screwed into one hole of the Y-axis carriage and also thread into the Y-axis piston and cylinder to prevent torque. Two holes were used to hang the Z-axis off the side for alignment.

Figure 7: Actuator Subsystem



A similar spacer block as the Y-axis support bar was used for the Z-axis except only a straight bar was needed. This spacer bar also has two holes that allow the Z-axis rail to mount into for alignment and to prevent torque.

The final component to be designed and installed was the block that would hold the pipette mount. The block had a through hole that allows it to be screwed into the Z-axis carriage. Once screwed in, the Z-axis piston and cylinder mount screws in underneath the block, securing it in all directions. The block has a screw hole on each of its three sides for the pipette holder to screw into. This gives the pipette nearly unlimited positioning options.

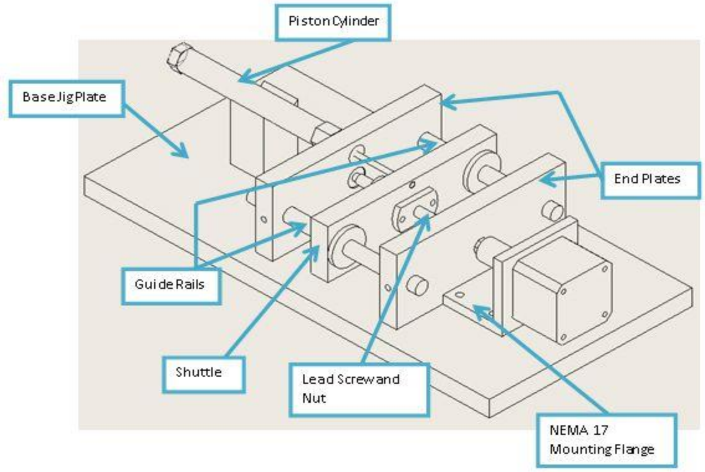
Pump and Lead Screw Subsystem Design

Each manipulator axis is hydraulically actuated. The Force required to actuate the stages is produced by a custom designed pump. This pump uses a lead screw assembly driven by a stepper motor in order to generate the extremely small fluid displacements to actuate on the required scale.

The design of the pump system starts with the lead screw selection. The lead screw is one of the primary sources of the system resolution, so immense focus was placed upon selecting a high precision lead screw. The ¼ inch – 80 threads per inch lead screw was identified as the optimal solution, since a full revolution of the lead screw results in forward motion of 0.3125 mm. This lead screw offered the best compromise in resolution to availability and workability. The one drawback to using a lead screw this fine is the thread can't handle a lot of axial force before stripping.

Lead screw selection drove the remainder of the process. Once the lead was determined, the required motor torque was calculated. The motor was oversized to ensure that the torque lost due to microstepping could be overcome. To connect the motor with the lead screw a misalignment compensating shaft coupling was used. Using this type of shaft coupling helps to mitigate alignment issues increasing manufacturability of the pump.

Figure 8: Lead Screw and Pump Subsystem



The lead screw in the design transfers the rotary motion to linear motion via the screw/nut interaction. The lead screw nut is therefore secured in a shuttle structure. This shuttle structure is connected to the piston cylinder to translate the linear motion into hydraulic force. Design of the shuttle accommodates the need for a central interface of all the moving components. This shuttle houses the lead screw nut, the piston mating threads and the two guide rail linear bearings. The guide rails are two steel shafts that run through the assembly to prevent rotation of the shuttle. These shafts mate with the shuttle using two linear roller bearings housed in the shuttle itself. These shafts are then clamped in the end blocks using setscrews. The end blocks provide a location for bearing housing, cylinder mounting and guide rail end clamping. These blocks are identical pieces that support the end of both rails and the lead screw in proper alignment to allow for smooth operation. The end blocks and various other support structures are mounted to a precision jig plate that serves as the pump base and main support structure for the system. The main drawback of this design is the precise alignment required for operation, resulting in increased machining time.

The pump system and the manipulator systems are connected by a closed hydraulic actuation system. The piston and cylinder selected for the pump were matched to the piston cylinder assemblies used for the manipulator. The selected arrangement has a smaller hydraulic area then that possessed by the manipulator. This favorable area ratio further increases the resolution of the system. But this area ratio also increases the load placed on the lead screw.

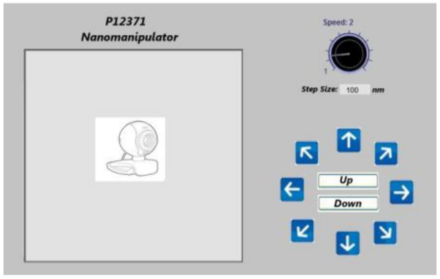
This creates a design problem where increasing your hydraulic amplification limits the lead screw selection. This tradeoff was addressed by sizing the pump piston cylinder to the lead screw. A larger area ratio was not used because the gains in resolution due to the lead screw greatly outweighed the resolution gains from an increased area ratio.

Computer Subsystem Design

The Computer control takes signals from either the user interface on the PC or a Joystick connected via USB and passes them to the microcontroller. The microcontroller sets or resets the appropriate pins on the Toshiba THB6064AH stepper motor driver chip to turn the stepper motor at different step sizes. Three individual driver chips and stepper motors were used, one for each axis of motion.

In order to achieve the resolution specification the Toshiba THB6064AH stepper motor driver chip was chosen since it supported the feature of micro stepping. Microstepping is a technology that allows a stepper motor to not just move one full step (our motor supported 200 steps per revolution, or 1.8 degree/step), but also less than that. The chosen driver chip allowed ½, ⅛, 1/10, 1/16, 1/20, 1/32, 1/40 and 1/64 microstepping, which allows the motor to turn as little as 0.03 degree/turn. In theory this would translate to a resolution of 11nm. The driver takes a clock input and a 3-bit signal input (M1 - M3) to internally calculate the step size where input 000 refers to ½ stepping and 111 to 1/64 stepping. The chip also takes a C/CW input signal to turn the motor clockwise or counter clockwise at every rising edge of the clock.

Figure 9: User Interface



Speed: 2

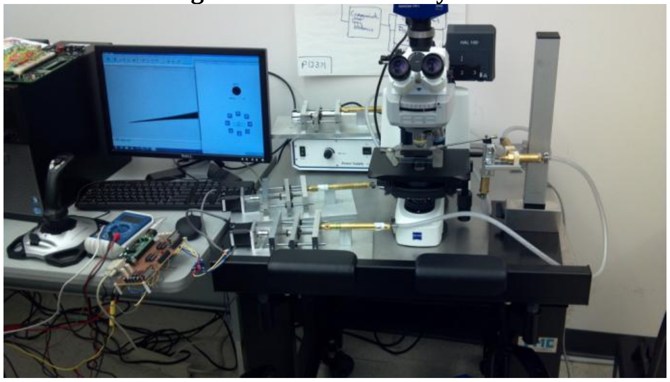
Step Size: 100 nm

The UI and the Joystick both have the capability of driving the motor at different speeds in all three axes. The different speeds are reflected in the 8 different excitation modes of the driver chip. The UI, shown in Figure 9, uses a dial to change the speed from 1 to 8, where 1 the highest resolution but the slowest speed. The user can set the speed and then move each axis individual through a button representation of a "joystick" on the User Interface. Straight and diagonal movement is supported in X and Y directions, while the Z can move up and down. The

USB Joystick allows for more accurate movement in 3 axes. By default the movement starts at the slowest setting, but it is adjustable through a switch on the joystick. Each time the head switch trigger is pushed up the speed increases by one step and decreases when it is pushed down. In addition to that it is possible to reset to the default by pressing the trigger button. Both, the UI and the Joystick create the same control signal. The control signal is created at a rate of 60Hz and follows the following format: ABBBC where A is the axis indicator, B is the 3-bit step size representation and C is the direction. As an example y0001 would turn the y direction motor at ½ step in counterclockwise direction.

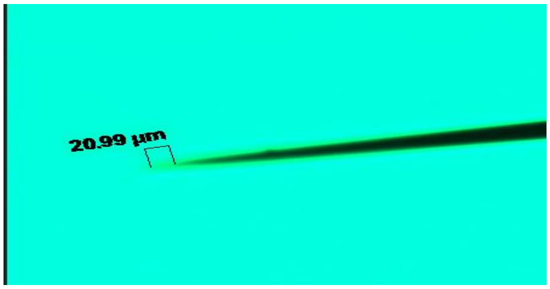
Once the signal is created either through UI or Joystick it is sent to the Freescale HSC12 microcontroller one character at the time via standard Serial connection (9600 Baude rate, 8 data bits, 1 start bit, 1 stop bit, no parity). The Microcontroller used the A and B output ports to send step size and direction signals to the driver chips. B[0-3] was used for the x-axis stepper motor, B[4-7] corresponded to the y-axis and A[0-3] assigned signals to the z-axis, all in the order of C/CW M3 M2 M1 from least significant to most significant bit. In addition to the control signal assignment the HCS12 also created a clock signal at 600Hz through the timer channel, which was also fed into each driver chip. Every time the controller received a signal it would set or reset the corresponding pins and then enable the identified axis driver chip for one clock pulse so that the stepper motor could turn. By default each axis is always disabled. Ports A[4-6] were used for the axis enable signal in the order of XYZ from the least significant to the most significant bit.

Figure 10: Assembled System



RESULTS AND DISCUSSION

Figure 11: Resolution Test



The primary goal of building a functional nanomanipulator was achieved. We realized computer controlled motion in all three axes via a joystick input. But because achieving full functionality took longer than anticipated, not all of the performance bugs were worked out of the system. One major performance detriment that effects ease of use is the system backlash. In the current configuration it takes 14 revolutions of the lead screw until the probe moves when changing directions of motion. Through testing the primary source of backlash was determined to the tubing that was used to connect the pumps and manipulator. When this tube was shortened to about 2” long, the backlash was reduced to a much more reasonable amount of 2 to 3 revolutions. The theory is that because the hose had a relatively large inner diameter, when pressure is applied to the fluid this hose would expand or contract significantly before the manipulator piston would move. But unfortunately the system becomes very unwieldy with the very short hose. A stiffer hose with a much smaller inner diameter should minimize the backlash, and the change in volume due to a pressure change would be much smaller. Given more time more tubing options would have been explored to reduce backlash.

Video feedback was achieved by using the microscope software. The live view has not yet been incorporated into the user interface. While this current setup is not ideal, it is functional and meets the specification of having live visual feedback at the control computer.

Using the visual program associated with the microscope we were able to measure the change in position of a pipette. Pictures were taken before and after movement, and then overlaid on top of each other. Then a measure tool that is part of the camera software was used to determine how far the tip of the pipette moved, shown in Figure 11. A step counter was used in the user interface to record how many steps the motor took. Then the displacement due to each individual step could be calculated to determine the resolution. The results of the various tests are shown in Table 3. The average resolution was 53nm with a standard deviation of 34nm. This exceeded the specification of 100 nm.

Table 3: Resolution Testing Results

Steps	**Delta X (µm)**	**Resolution (nm)**
263	20.99	79.8
85	3.25	38.2
266	17.53	65.9
324	36.08	111.4
750	10.34	13.8
825	22.78	27.6
908	28.89	31.8
	Average:	**53**
	Standard Deviation:	34

Our limits of travel were found to be 0.9cm, which met our spec of having greater than .25 cm of travel. Our specifications of sampling rate of 60 Hz, supported control software, and ability to mount a standard pipette holder were all achieved. The manipulator size and weight constraints were not achieved, however after discussion with our client it was deemed acceptable. The manipulator size was 10 x 10 x 10 cm; only slightly larger than 8 x 8 x 8 cm. The weight was 760 grams, where as the specification called for 550 grams.

The cost goals were met well. Our system cost as built cost us $1720.61, slightly exceeding our ideal specification but coming well within the marginal value. The development cost, which includes spending on spare parts as well as parts not used in the final configuration was $2152.81. This was under our total budget of $2500.

CONCLUSIONS AND RECOMMENDATIONS

The scope of the entire project was quite large, involving mechanical design of two precision subsystems, design of a computer control system, and integration of all of these subsystems. We were able to significantly reduce the cost of the mechanical system. Also achieving computer control of a hydraulic manipulator was something that has never been done before. Considering the scope of the project and the compressed timeline involved in completing it, having a fully functional system is a great success.

The mechanical system suffers from a large amount of backlash. Each time the direction of movement is reversed the lead screw has to rotate 14 times before the probe begins to move again. We were able to determine through testing of the various subsystems that the majority of the backlash comes from the hydraulic system. We believe that this backlash is due to the static friction present in the hydraulic system. Since static friction opposes the direction of motion of an object a dead zone is created where a significant pressure change in the hydraulic system is required to overcome this friction. A diaphragm seal, such as the seal used in the Narishige manipulator (a commercially available manipulator that was available to us) would greatly reduce this static friction. We did not go with this design due to the lack of off the shelf parts available. A more customized and involved design would be required to implement the diaphragm seal, but would result in better system performance. There were also some inconsistencies in the ratio of revolution of the lead screw to movement of the probe. Sometimes the probe would move a small amount with a revolution then suddenly move a large distance. We believe that this behavior was also a result of the static friction and would be minimized with the diaphragm seal configuration.

Although the mechanical system fit nicely under a microscope, a future goal would be to reduce the size of the entire system. The subsystems are rather large and reduce the portability of the entire system. By working to find smaller piston and cylinder assemblies, or attempting the diaphragm hydraulic system mentioned before it would be possible to reduce the size and weight of the system. In addition the system would be designed in a more robust manner to handle machining errors.

ACKNOWLEDGMENTS

The project team would like to give special thanks and recognition and acknowledge the contributions received in process of course. This project would not be possible without the continuing support and guidance of the following people.

- Dr. Michael Schrlau and the NanoBio Interface Research Group, primary customer and adviser.
- Michael Bady and Eppendorf for the donation of a commercial manipulator.
- Rob Kranyk and the RIT ME Machine Shop for their help and guidance.
- RIT Office of Sponsored Research for their financial support