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14. ABSTRACT

Electromechanica Inc. was tasked with researching and developing a proof of concept robot tool for in-situ pipe inspection of fleet piping. Electromechanica has designed and fabricated a proof of concept robot tool based on a pneumatically actuated peristaltic motion. This motion is accomplished by the use of inflatable pneumatic grippers, as well as a novel flexible pneumatic cylinder capable of actuation in a variety of articulated positions. Various representative piping systems were used to successfully test locomotion and guidance of the system.

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Abstract

Electromechanica Inc. was tasked with researching and developing a proof of concept robot tool for in-situ pipe inspection of fleet piping. Electromechanica has designed and fabricated a proof of concept robot tool based on a pneumatically actuated peristaltic motion. This motion is accomplished by the use of inflatable pneumatic grippers, as well as a novel flexible pneumatic cylinder capable of actuation in a variety of articulated positions. Various representative piping systems were used to successfully test locomotion and guidance of the system.

Contents

Introduction

Fleet piping systems are complex, space constrained systems which are difficult to inspect using standard external inspection techniques. Pipe lagging as well as limited access make external access prohibitively expensive and difficult; see Figure 1 and Figure 2.

Figure 1 - Complex, space constrained piping

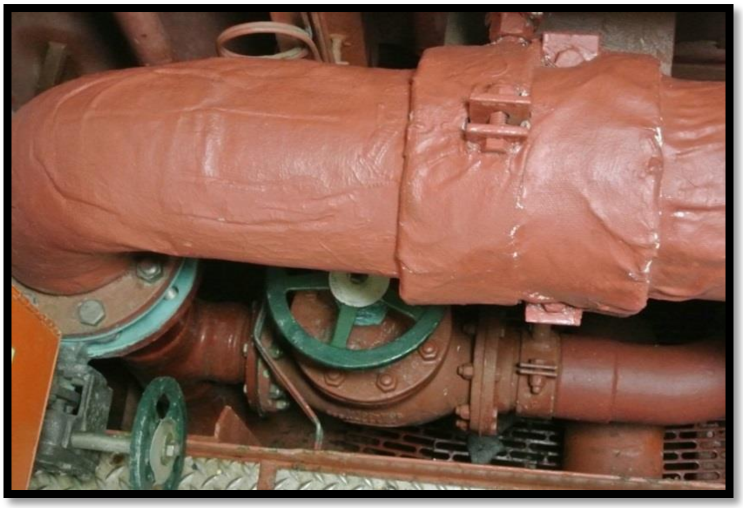


Figure 2 - Pipe lagging

To facilitate inspection it was desired that a means of internal inspection be researched and developed. Electromechanica Inc. has been tasked with developing a robotic tool which will eventually deliver a sensor package capable of real-time corrosion/erosion and pipe wall measurements. Implementation of this system will allow for fleet preventative maintenance (PM), ensuring that possible failures are detected and replaced before they occur.

Discussion

Project kickoff, mock piping, and gripper development

Electromechanica received funding for the project on 1 August 2013 in the amount of $149,902.00 for a 6 mo. period.

A mock piping test track was erected consisting of segments of schedule 40 PVC piping (Figure 3).

Figure 3- 3 in. Mock piping

Grippers were designed and fabricated integrating COTS solenoid valves for air flow control (Figure 4).

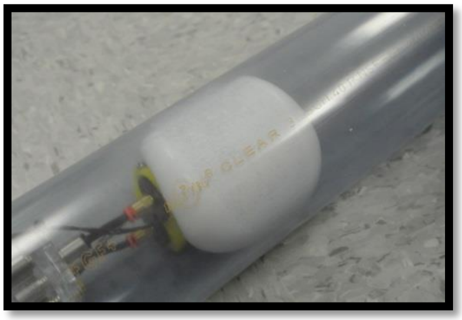


Figure 4 - Grippers inflated

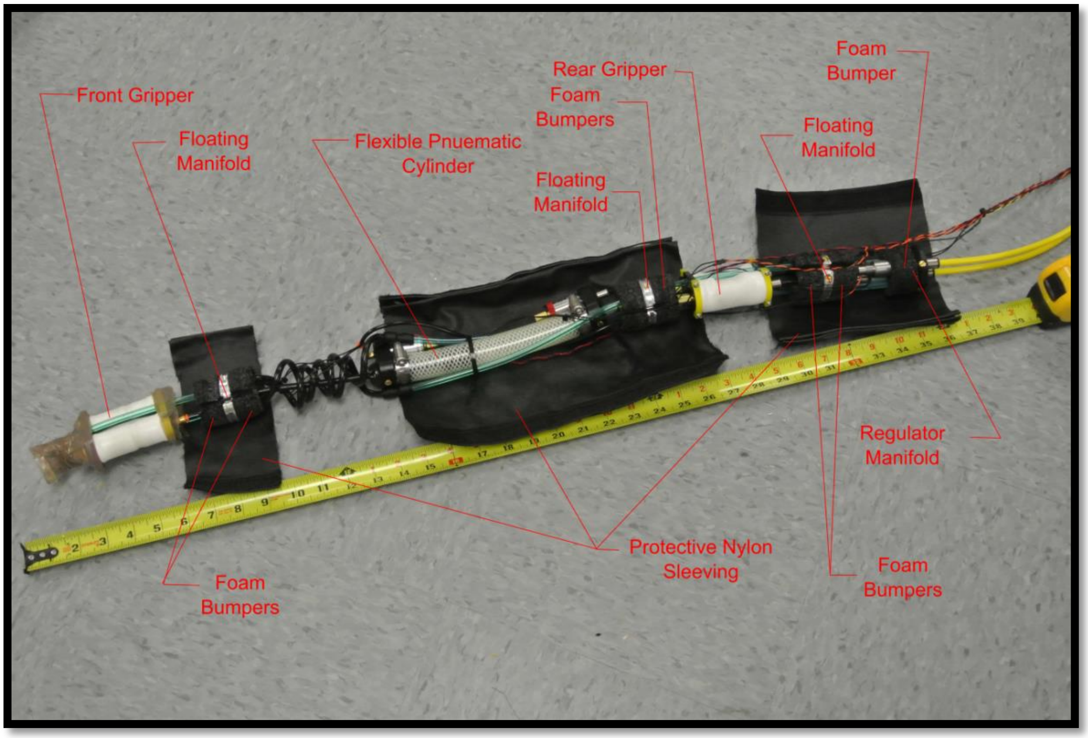


Figure 5 - Robot assembly

Flexible Cylinder

The robot utilizes a flexible pneumatic cylinder which provides forward and backward motion while negotiating various bends in conjunction with the grippers. The prototype cylinder was tested to evaluate capability of operating in tight bends. This was accomplished by fixing each end to form a 90° bend and actuating the cylinder (Figures Figure 6 and Figure 7).

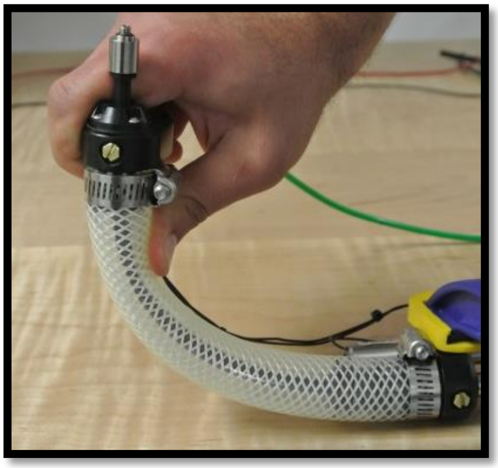


Figure 6 - Actuator retracted

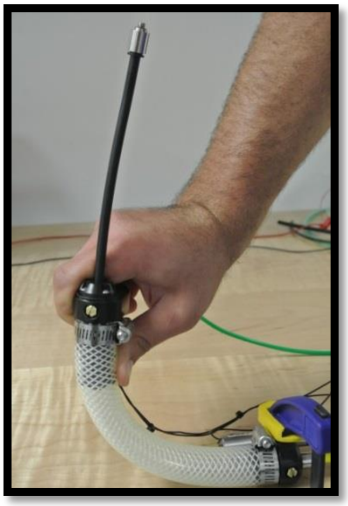


Figure 7 - Actuator full extension

Manifold development

Floating air manifolds will deliver air to the entire robot and to each individual component (Figure 9). Additionally air regulator bays were developed to control two set pressures of airflow through the entire robot. Pressure regulated air is supplied to the various pneumatic actuating components on the robot (Figure 8).

Figure 8 - Valve manifold

Figure 9 - Floating distribution manifold

Prototype hardware testing

Initial testing revealed the robot’s ability to successfully navigate through a 3 in. diameter pipe mockup horizontally and vertically.

Gripping force testing

Pulling in an axial direction the gripper assembly achieved 36.33lbs of gripping force @ 20 psi (Figure 10).

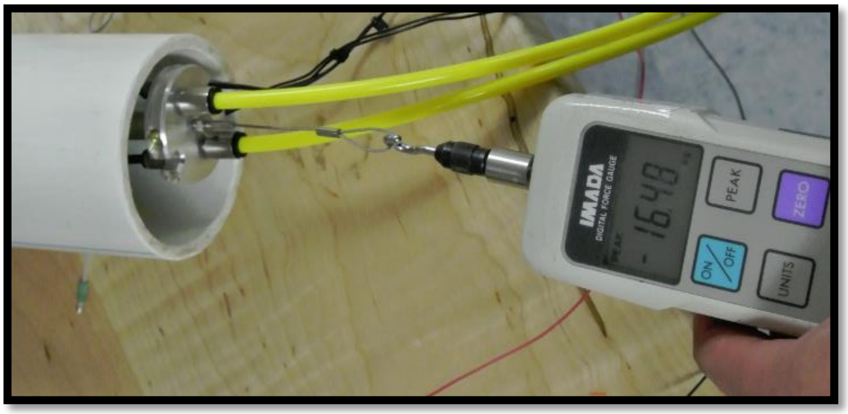


Figure 10 - Gripping force test

Forward motion modification

Skids were added to the robot’s grippers reducing the total cycle time of forward and backward linear motion. They allow the robot to move forward without causing any drag due to the bags being partially inflated (Figure 11).

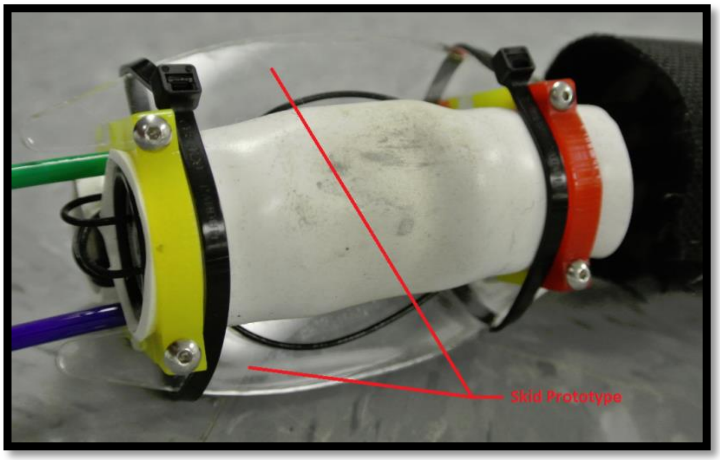


Figure 11 - Gripper sleds

Basic automated motion using software

The robot successfully ran on auto pilot through a straight section of pipe in both forward and reverse motions. The optimal travel speed was determined by adjusting the command cycle times. Flow rate usage vs. rate of speed was also obtained from this exercise.

Mock piping 2.0

Lab grade borosilicate glass pipe was used for mock piping 2.0 structures and testing. The glass aids in evaluating troublesome situations to clearly verify any problems in challenging pipe geometries (Figure Figure 12, Figure 13 and Figure 14).

Figure 12 - Navigation through opposing elbows test

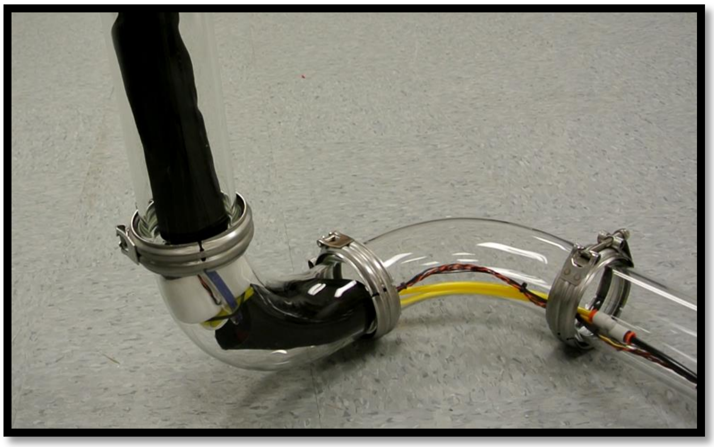


Figure 13 - Navigation through perpendicular elbows test

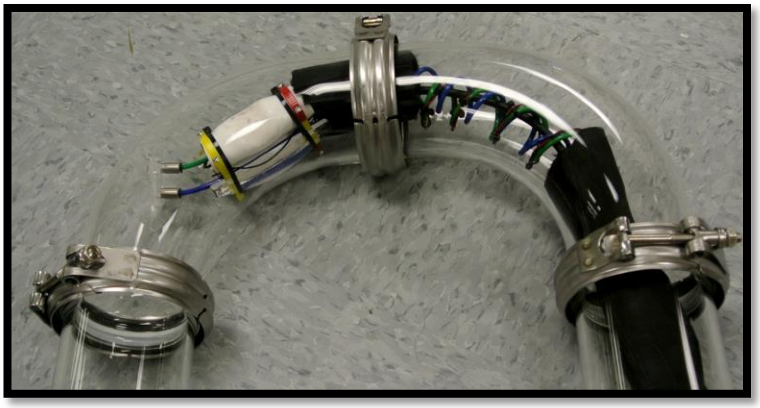


Figure 14 - Navigation through inline elbows test

Improved gripper design

During testing, unrestricted expansion of the bladders decreased resultant axial force. A new ‘X’ wing design was developed to constrain bladder inflation and provide bearing surfaces during motion and help center the module in the pipe. The ‘X’ shaped skid allows the silicone tubing of the grippers to inflate in a controlled geometry which decreases inflation/deflation times (Figure 15).

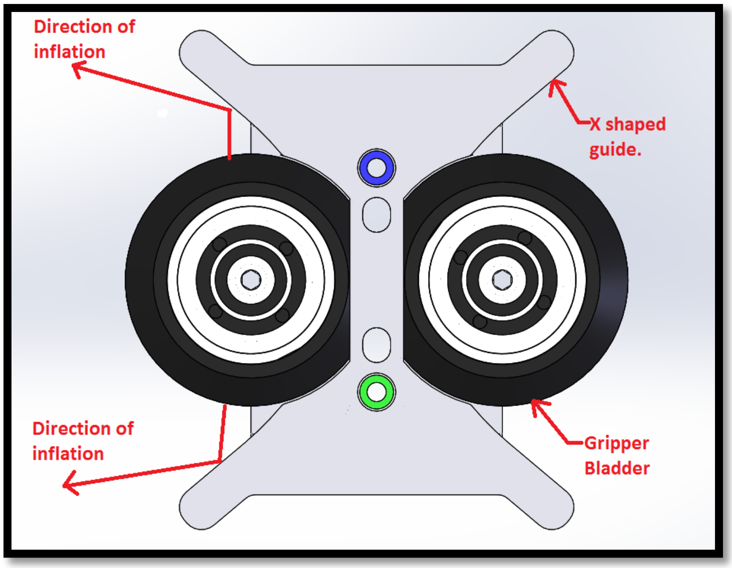


Figure 15 - Inflation diagram

A gripper snout was developed for both the front and rear of the robot to aid in smoother motion of the gripper around curves, tees, elbows, etc. (Figure 16).

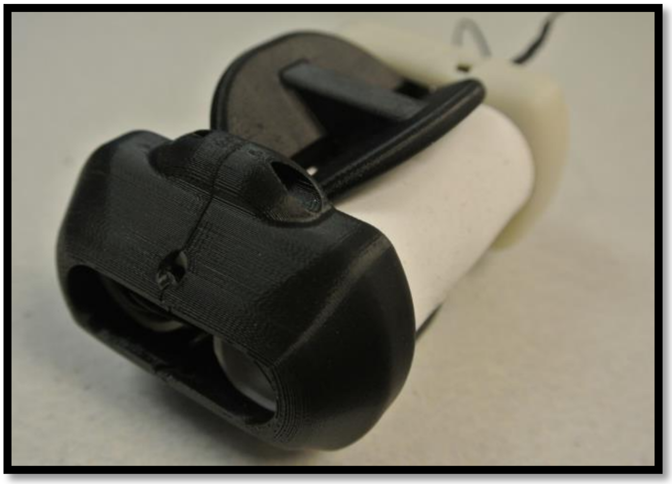


Figure 16 - RP part of the gripper main body

Gripper force testing 2

The new design allowed for higher pressure which allowed the gripper to achieve 30lbs of axial force (Figure 17).

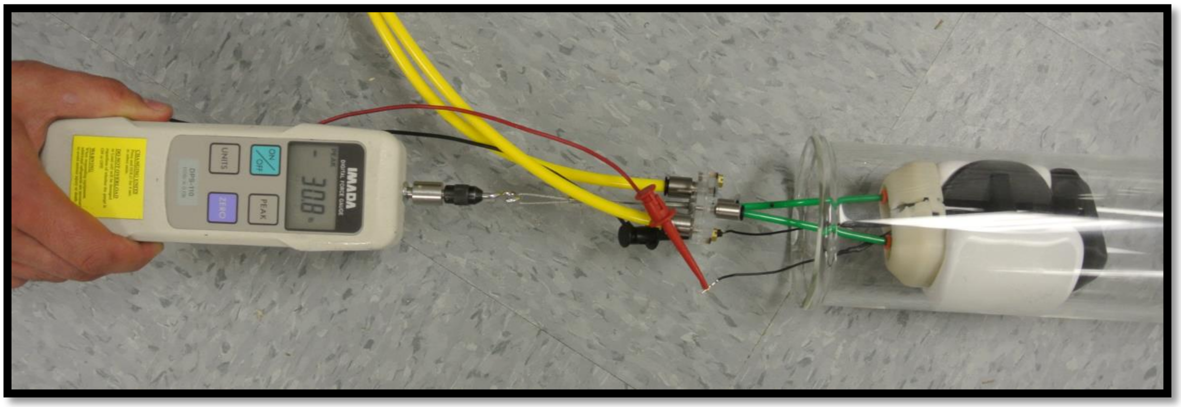


Figure 17 - Grip force testing

Second set of RP parts

Based on the success of the new ‘X’ wing design a second set of parts were fabricated.

PCB control module

A printed circuit board (PCB) assembly was designed and built to facilitate remote control of the robot. This module is composed of two PCB assemblies; a controller and a valve driver. The robot will be connected via a single tether and it is desirable to minimize the number of conductors in that tether to reduce weight and increase flexibility. The Ethernet PCB can be seen in Figure 18**Error! Reference source not found.**.

Figure 18 - Ethernet controller PCB

The valve driver PCB includes a microcontroller and valve driver electronics to control the pneumatic solenoid valves on the robot. The valve driver is currently capable of driving twelve (12) solenoid valves. The valve driver PCB can be seen in Figure 19.

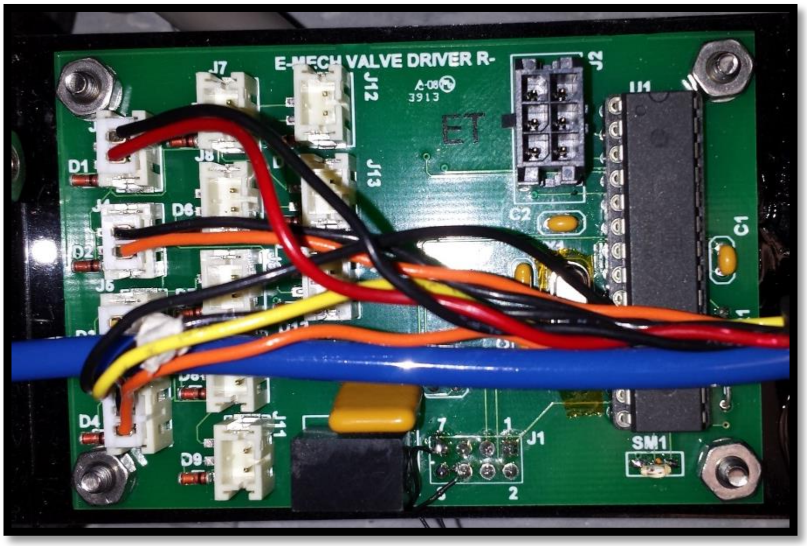


Figure 19 - Valve driver PCB

Power over Ethernet injector PCB

A custom PCB was designed and built to inject 48VDC power into the Ethernet cable to supply power to the robot, as shown in Figure 20. The circuit design includes a microcontroller which via USB, can toggle the power to the robot. This is an important feature for development, allowing the control program to programmatically toggle power to the robot *in-situ*.

Figure 20 - PoE Injector PCB

48VDC has been chosen as the supply voltage due to the long lengths of cable between the supply and the robot. It has been calculated that 48VDC will provide sufficient voltage margin to adequately supply the required power to the robot. Total power requirements were approximated, for additional future hardware.

Controller Module Pod

A ‘pod’ enclosure was designed to improve maneuvering capability and offers protection for the electronics against the pipe environment (Figure 21).

Figure 21 - Controller pod

The pod is attached to the aft end of the robot which additionally serves as the connection point to the robot's tether. The tether serves as an umbilical between the operator control station and the robot.

Pilot cone

A pilot cone was designed to improve maneuverability through the pipe. Prior to this design the robot had a flat manifold which impeded movement during testing (Figure 22).

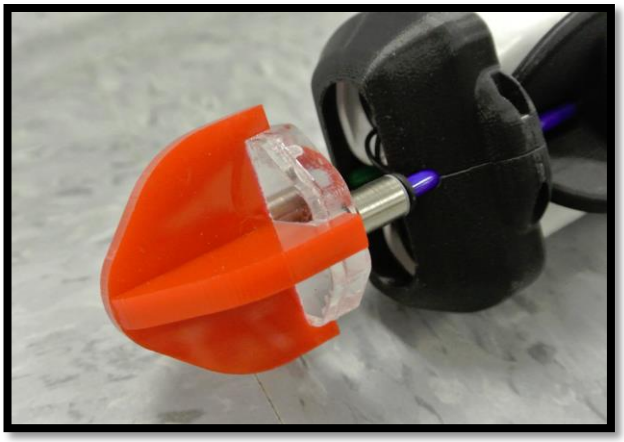


Figure 22 - Pilot Cone

Inline check valves

During testing it was observed that when one gripper was active and the second gripper activated, the first gripper bladder would slightly deflate, while also loosing gripping force, resulting from a transient decrease in pressure. Adding check valves minimized this effect by isolating each gripper (Figure 23).

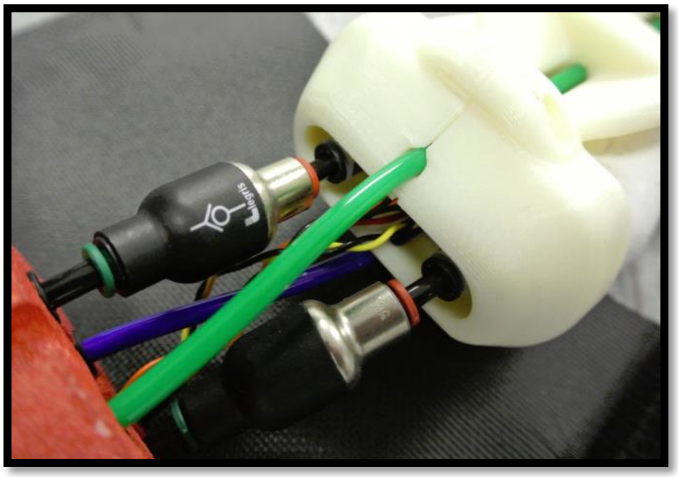


Figure 23 - Inline check valve

Operator control unit

Testing and software development for the robot required the development and building of a control panel. This control panel consolidates multiple items into a single compact case, those items being:

- Emergency stop for air and power
    - All system air vented during an Emergency stop event
- Power over Ethernet injection
    - Custom PCB to inject robot power into the Ethernet cable
- System power supply

The control panel provides a convenient central location for items external to the robot, as shown in Figure 24 and Figure 25.

Figure 24 - Control panel

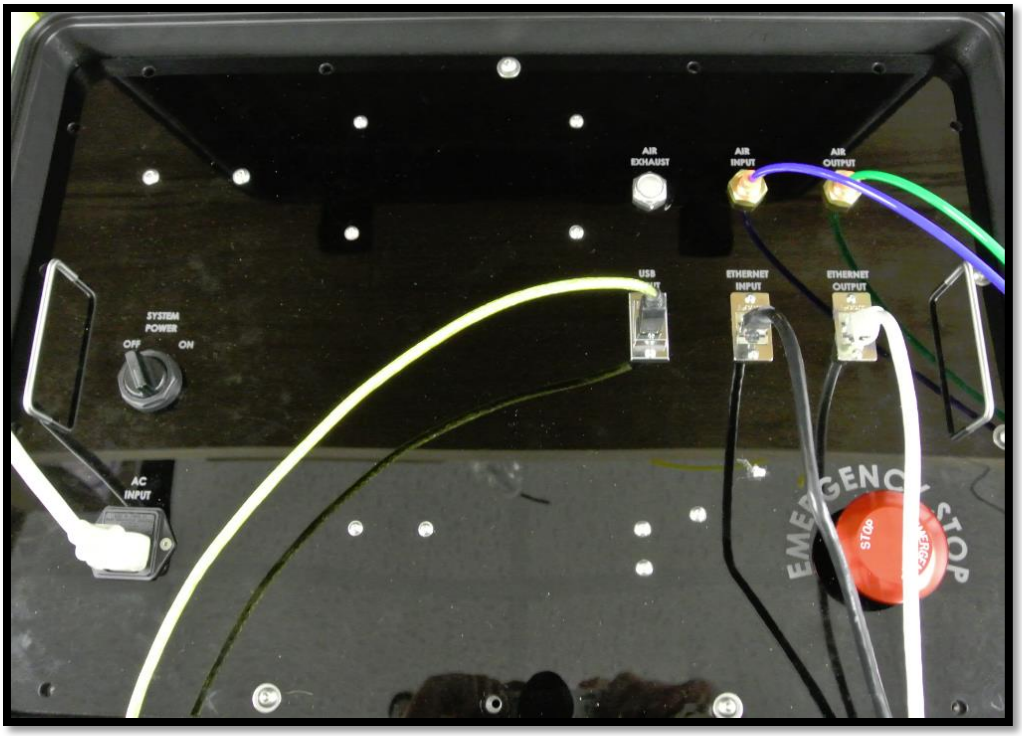


Figure 25 - Control panel, with connections

Multiple degrees of freedom coupling

A flex joint with multiple degrees of freedom replaced the previous rigid connection to reduce stress between the piston rod and front manifold (Figure 26).

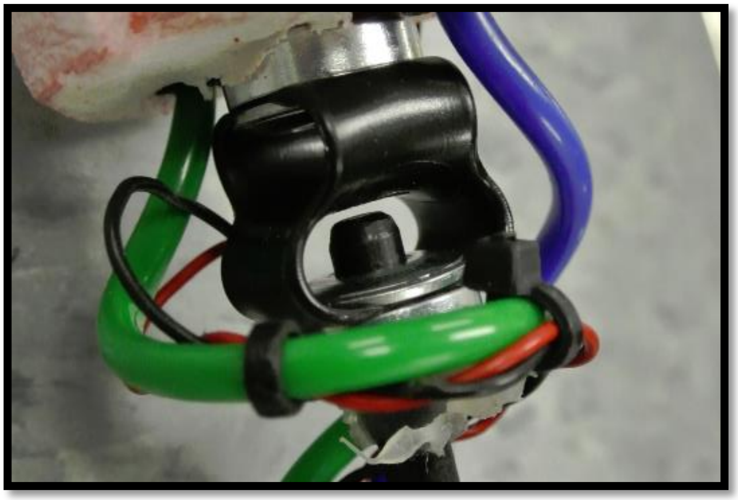


Figure 26 - Flex joint

High pressure manifold

A high pressure manifold (Figure 27) was fabricated and its structural integrity tested to 500psi in which it successfully maintained pressure without failure.

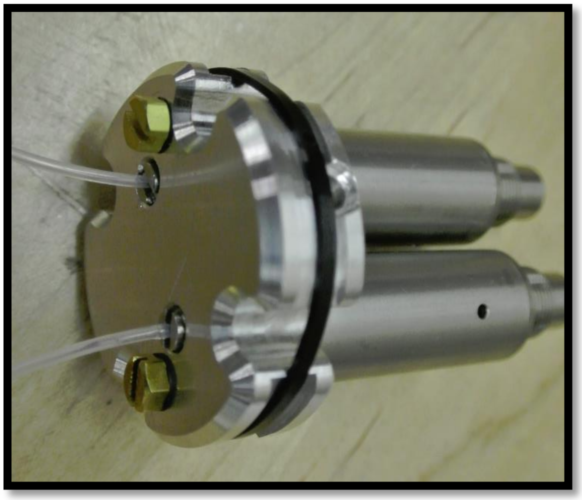


Figure 27 - FEP High pressure manifold

High pressure flow test

Based on a requirement of 0.63cfm and 115psi at the robot after pressure losses a series of tests were conducted comparing two FEP tubes and a single nylon tube. The nylon tube was selected above all as it showed lower pressure drop and increased flow margin (Figure 28). Nylon also represents several benefits over FEP being more flexible, tougher and can be used with commercially available high pressure compression fittings.

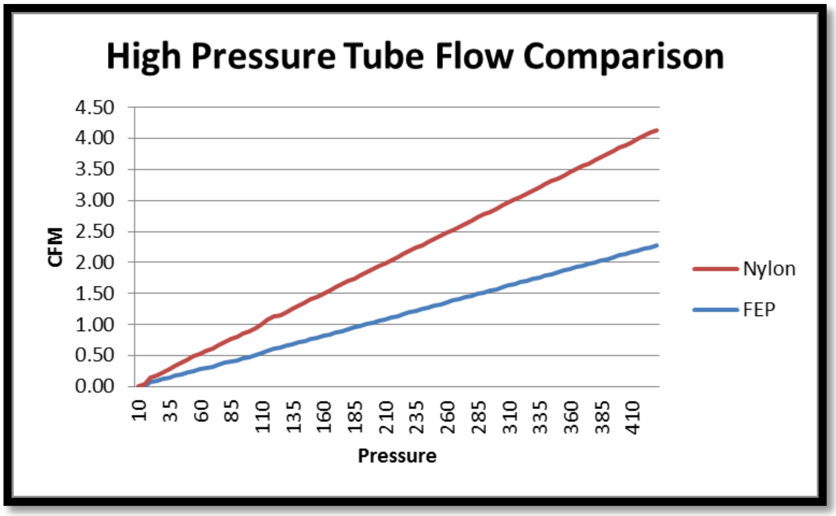


Figure 28 - Graphical flow comparison

Ethernet controller board connection troubleshooting

During testing of the Ethernet communications to the robot, it was found that the Ethernet controller would occasionally reset itself, dropping connection to the PC using both TCP and UDP protocols. After extensive testing it was found that the cause of the issue was very fast power glitches in the 3.3V supply. These glitches were caused by the instantaneous current spikes associated with the driving of the solenoid valves. A revised Ethernet controller was developed to remedy the problem.

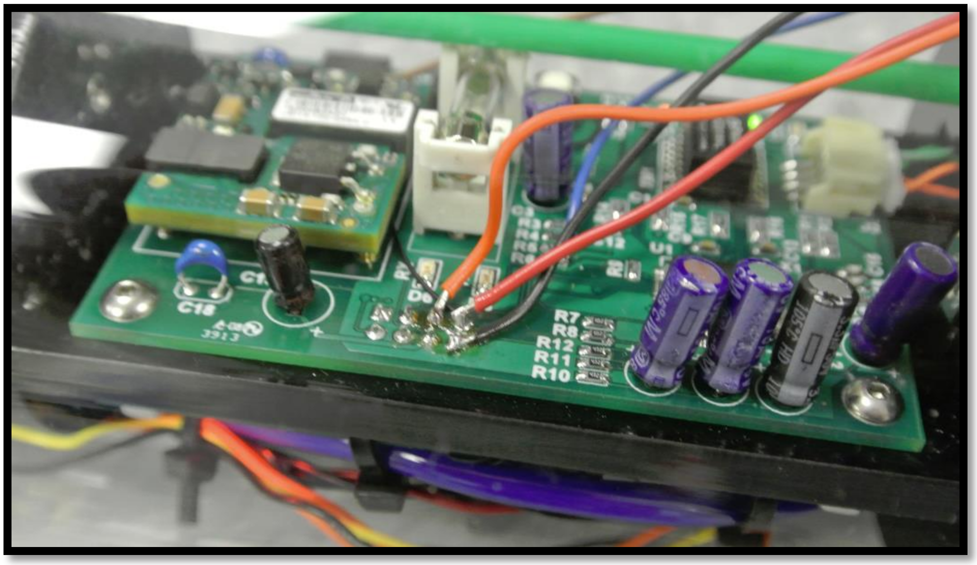


Figure 29 - Controller module troubleshooting

Steering head development

Two steering heads comprised of the same components were developed the only difference being the location of the pneumatic muscles on the head. The range of motion between the two was analyzed for optimal flex/travel (Figure 30).

The steering head consists of a tail regulator manifold which reduces the high pressure line down to 40psi, a solenoid valve bank for controlling each muscle individually, and a pneumatic muscle assembly allowing 8 possible directions (Figure 30).

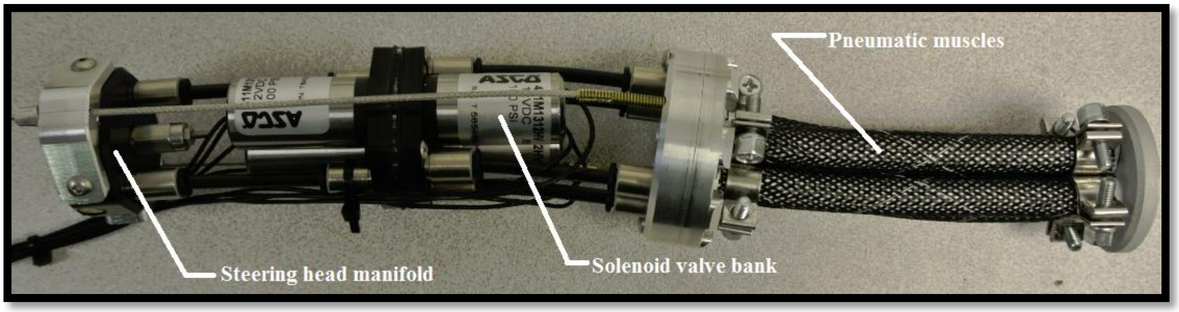


Figure 30 - Steering head assembly

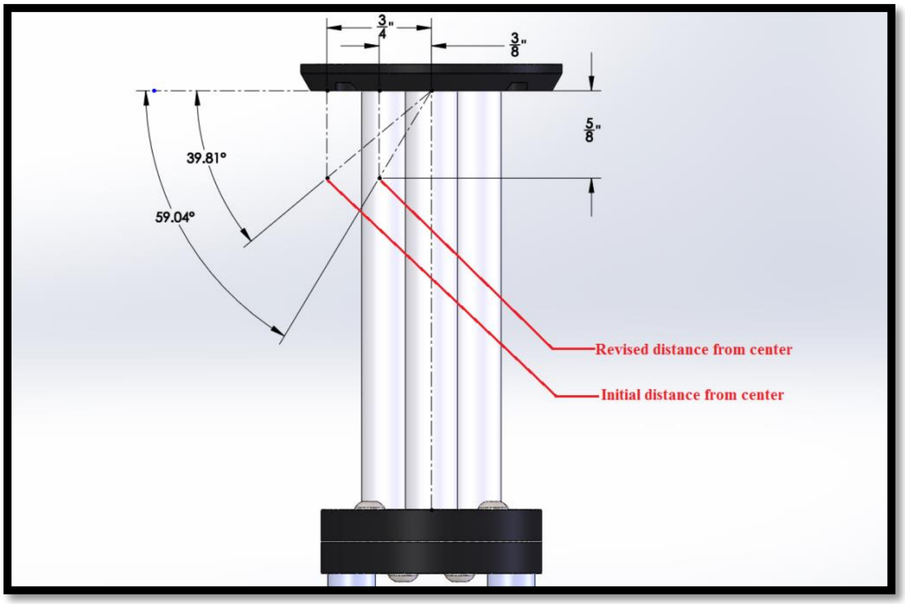


Figure 31 - Angle change representation

Linkage strain reliefs

During the manual extraction direction changes (bends) in particular increase friction as they force more of the robot into contact with the inner wall of the pipe (Figure 32). This friction can cause excessive stress on the tube fitting connections and wiring, which may fail if excessive pull force is used when extracting the robot.

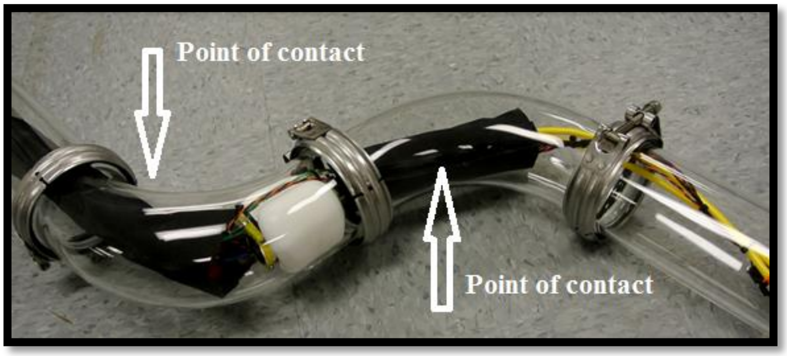


Figure 32 - Friction points of contact

Stainless steel rope linkages were attached between the manifolds to act as a strain relief. When tension is applied to the tether these linkages will bear the load and prevent force from being transmitted through pneumatic tubing or wiring (Figure 33).

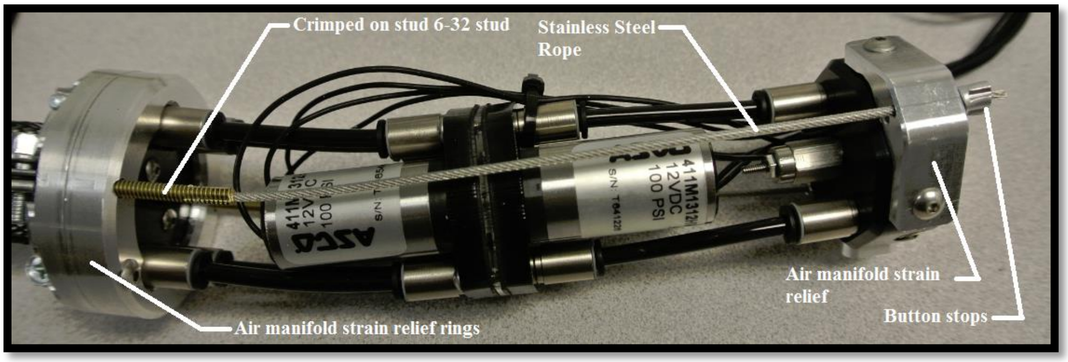


Figure 33 - Steering head assembly

Control module R2

Another pod enclosure was designed and fabricated using 6061-T6 aluminum. The new pod is machined out of a single piece of aluminum which makes it much more robust than the previous acrylic iteration. The new version also allows for improved wire strain relief system than the previous design.

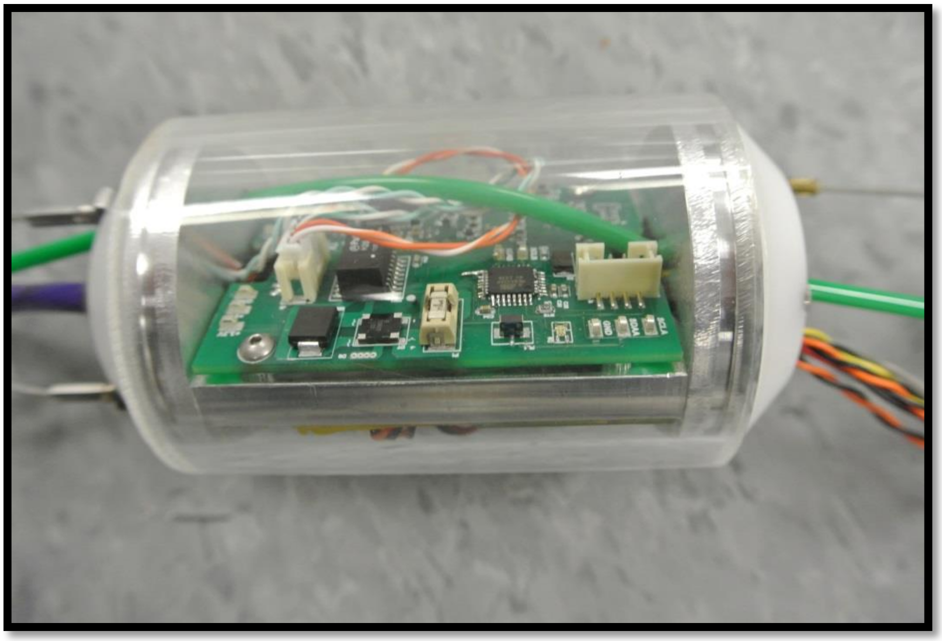


Figure 34 - Control module

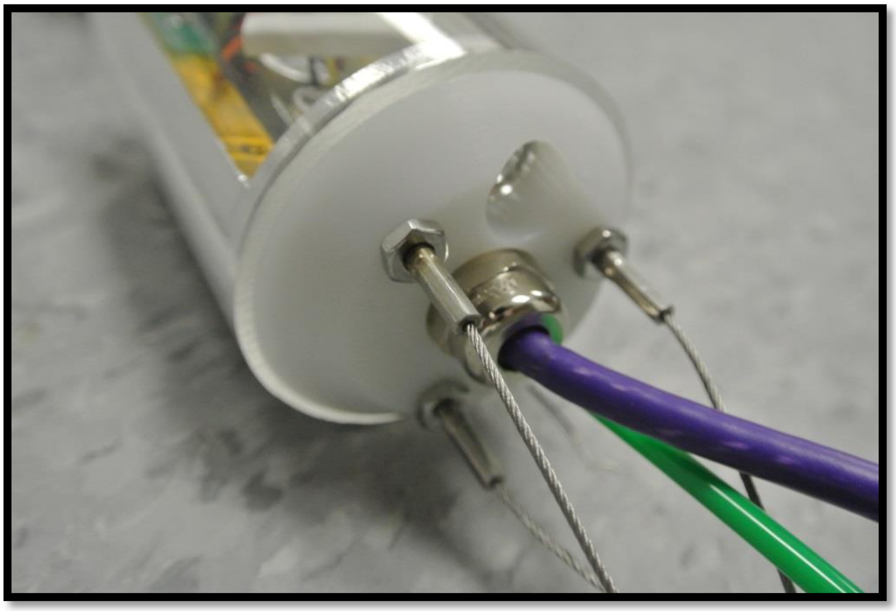


Figure 35 - Control module cable strain relief

Power over Ethernet Injector Redesign

A new iteration of the Power over Ethernet (PoE) injector has been designed. This new design includes higher accuracy current measurement for accurate profiling of the robots power requirements.

Figure 36 - PoE Injector

Ethernet Control Module Redesign

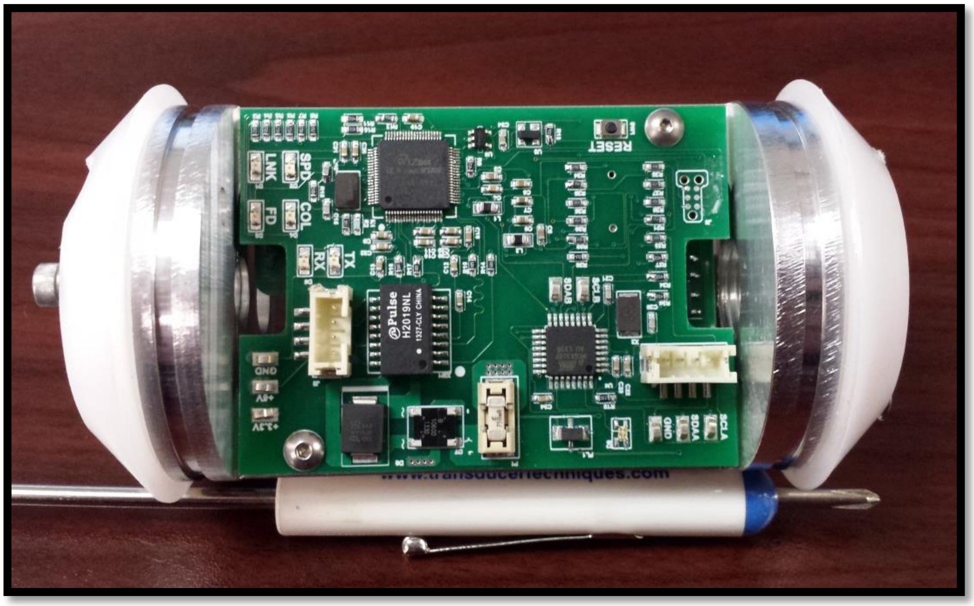


Figure 37 - Ethernet Module, Ethernet PCB

Figure 38 - Ethernet Module, Valve Driver PCB

During testing of the first Ethernet Control Module (ECM) it was observed that the module occasionally disconnected from the host PC over Ethernet, while using the TCP or UDP protocols. Troubleshooting was conducted, and it was found that the cause of the disconnection was related to instantaneous power glitches on the 3.3V and 5V power supplies. The glitches were related to the instantaneous current spikes experienced when turn on of the solenoid valves. These occasional glitches would cause the logic components to briefly lose power, which in turn would drop the Ethernet connection.

Pneumatic Gripper Closed Loop Control

For initial testing, inflation of the gripper module has been accomplished using a regulated low pressure, and a single 3-way valve allowing the gripper to be fully inflated and pressurized to the system pressure, or to be fully deflated. This is undesirable for multiple reasons, two of which being:

1. Gripper pressure is regulated to a set pressure above atmosphere; grippers will not be able to transition to/from a pressurized environment.
2. Regulators create additional bulk, in a space constrained environment.

To facilitate testing a mock gripper with an integrated pressure sensor was designed as seen in Figure 39. A 10BAR rated pressure sensor was integrated into the assembly to monitor pressure during inflation.

Figure 39 - Mock Gripper Assembly

A system was setup such that the gripper would be intelligently inflated. This system made use of a microcontroller, and valving. The microcontroller would monitor the change of pressure

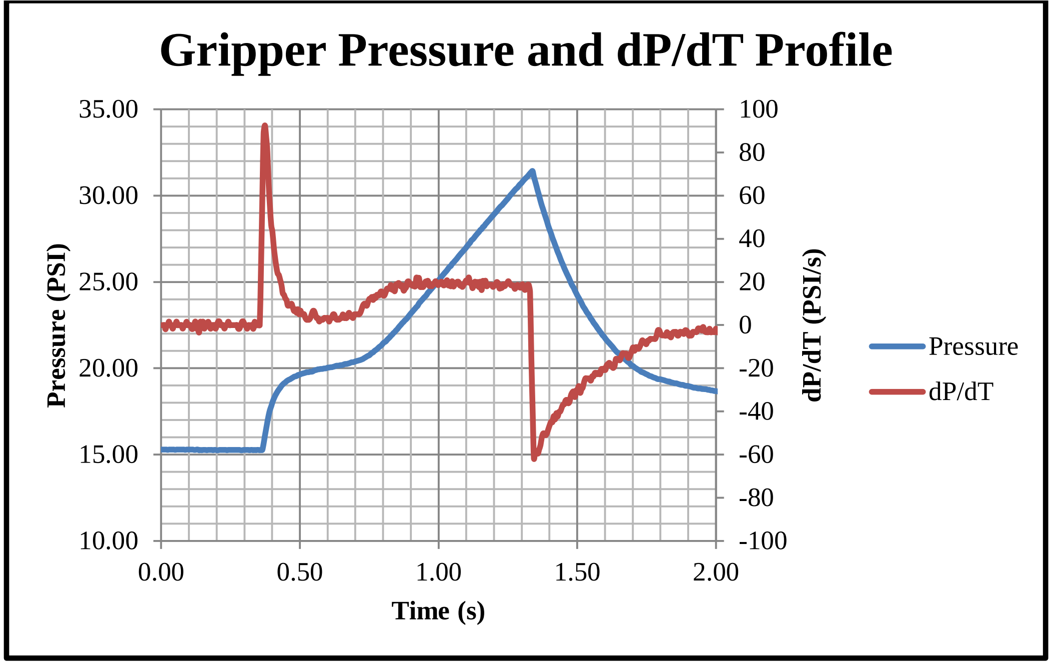


Figure 40 - Gripper pressure and dP/dT profile

Gripper Life Testing

Given the successful use of the silicone gripper modules, it was desired to investigate the expected life of the silicone grippers in the particular application. It was thought that repeated expansion and deflation of the gripper could be detrimental to the material, causing premature failure of the robot.

To perform the testing a small test setup was built, to cycle the gripper until failure, shown in Figure 41. In this system, the microcontroller development board controls a single valve which fills and deflates the gripper module located in the pipe. Pressure feedback is read via a small pressure sensor.

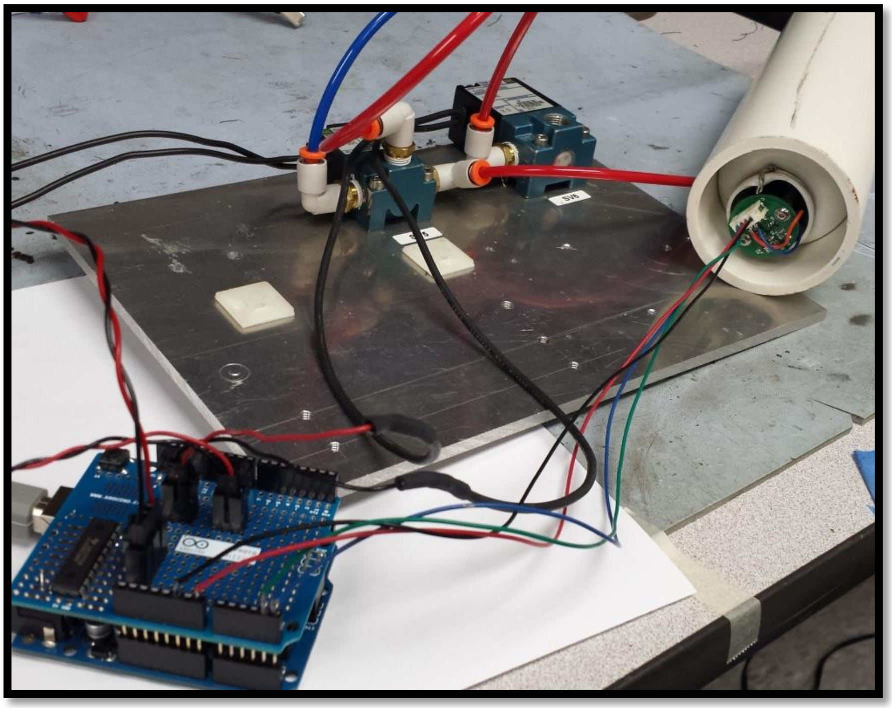


Figure 41 - Life testing setup (omits LCD screen)

The test process is as follows:

1. Gripper inflates
2. Check for pressure greater than 20PSI, if not, fail test
3. Gripper deflates
4. Check for pressure less than 3PSI, if not, fail test
5. Repeat

The test setup included a small LCD screen to prompt the operator if a failure occurred, it can be seen in Figure 42, which shows a typical output of the LCD.

Figure 42 - LCD output

Initial testing was performed using soft stainless steel wire as a binder to hold the silicone tubing in place. Testing was conducted, and it was found that the gripper lasted approximately 5000 inflate/deflate cycles. Upon inspection, it was determined that failure was associated with the repeated rubbing of the silicone on the stainless wire, as shown in Figure 43.

Figure 43 - Gripper silicone failure

To prevent rubbing, a small piece of abrasion resistant nylon sleeve was placed below the stainless steel wire, preventing the silicone from coming in contact with the stainless steel wire. This method greatly increased the performance of the gripper, allowing over 47,097 inflation/deflation cycles. Testing was stopped, as it is believed that at this point 47,000 cycles is more than adequate for the application. Given a stroke length of 5.5in, this equates to a traveled distance of over 21,500ft or just over 4 miles. The gripper can be seen in Figure 44.

Figure 44 - Gripper after 47,097 successful cycles.

Robot Life Testing

Given the favorable performance of the current robot design, it was desired to perform a life cycle test to identify potential mechanical failure points in the robots design. The testing consisted of the robot traveling vertically up and down in 16ft with sensors integrated on either end to inform the host program to change the robot's direction.

Figure 45 – Sensors

Figure 46 - Robot in pipe

During testing many issues arose, mainly the high to low pressure regulators consistently failing. The most detrimental failure while testing was the batch of regulators which worked fine for a finite amount of time and then suddenly dropped pressure. This caused pressure spikes/drops in the system which led to catastrophic failures of the grippers.

Another failure was the piston seals O-ring cores, inside of the flexible cylinder, were popping off their seats allowing air to blow by and causing the piston to cease. The solution to this problem is to place reinforcements around the core, forcing the O-ring to stay put in its seat (Figure 8).

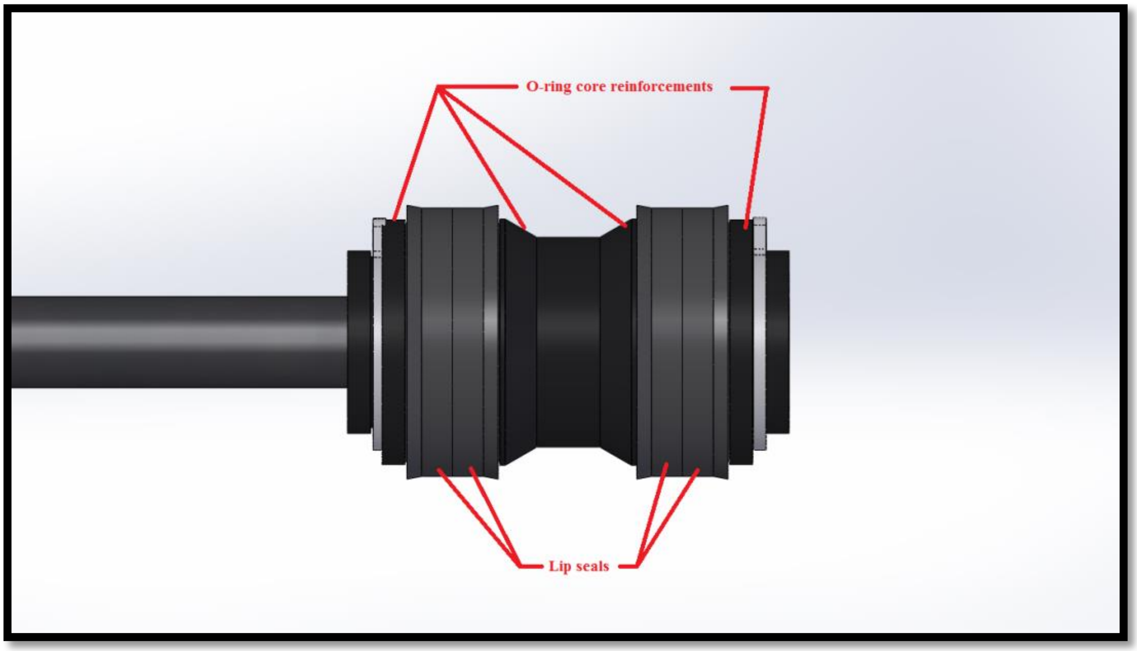


Figure 47- Lip seal reinforcement

Alternate gripper bag material research

During the robot’s lifecycle test the gripper bags were determined to be too temperamental when dealing with pressure swings. Comparing silicone to other materials led to possible interest in using latex as an alternative material. Latex and silicone are very similar when comparing their physical properties, when compared chemically latex outperformed silicone.

Tests were conducted to determine if this material would be worth venturing into. Latex is very resilient and maintained pressure and grip with a puncture in the sleeve at 60psi.
The latex performed the same as silicone in axial gripping force at the same pressure (Figure 12).

Figure 48 - Gripping force test 2

One of the biggest advantages of latex over silicone is its elastic deformation in which the same cannot be said for silicone which tends to deform and weaken if over inflated.

Alternate Gripper Solutions

Given the temperamental nature of the current gripper design a COTS solution was desired. After some extensive research the use of inflatable seals was determined to be the best path of progression.

The biggest advantage this seal has to offer is the solid ribbed block sitting at the crest of the seal. The block allows the seal to be rugged and the ribs aid in pushing any residues away from the contacting face. The seals profile allows up to 5/8” of travel (Figure 49).

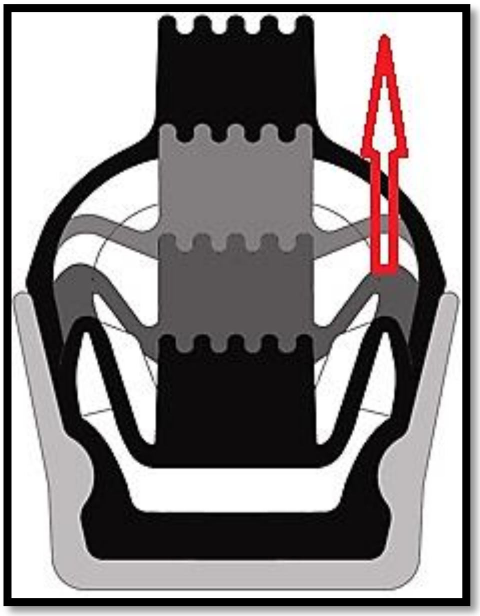


Figure 49 - Seal inflation

Gripper Redesign Axial Force Test

A grip force test was conducted to establish the current designs capabilities. The seal acquired for evaluation was used in a 5” pipe and achieved a gripping force of 100lbs+ at 30psi. The force gauge reached its maximum limit and the gripper continued to hold without budging (Figure 50).

Figure 50 - Peak force

Omnidirectional Vision Sensor

In order to inspect the pipe surrounding the robot the vision system needs to be able to view 360°. This will be achieved by pairing a high resolution camera with an omnidirectional vision sensor (ODVS). Two ODVS’s are currently being considered for the robot, the Kogeto ODVS and the Accowle ODVS as seen in Figure 51 and Figure 52 respectively.

Figure 51 - Kogeto omnidirectional vision sensor

Figure 52 - Accowle omnidirectional vision sensor

The ODVS uses either conical or parabolic mirrors in order to reflect items which are perpendicular to the viewing angle of the camera. The Kogeto ODVS uses two parabolic mirrors to reflect its surroundings as seen in Figure 53. The Accowle sensor uses one parabolic mirror as seen in Figure 54.

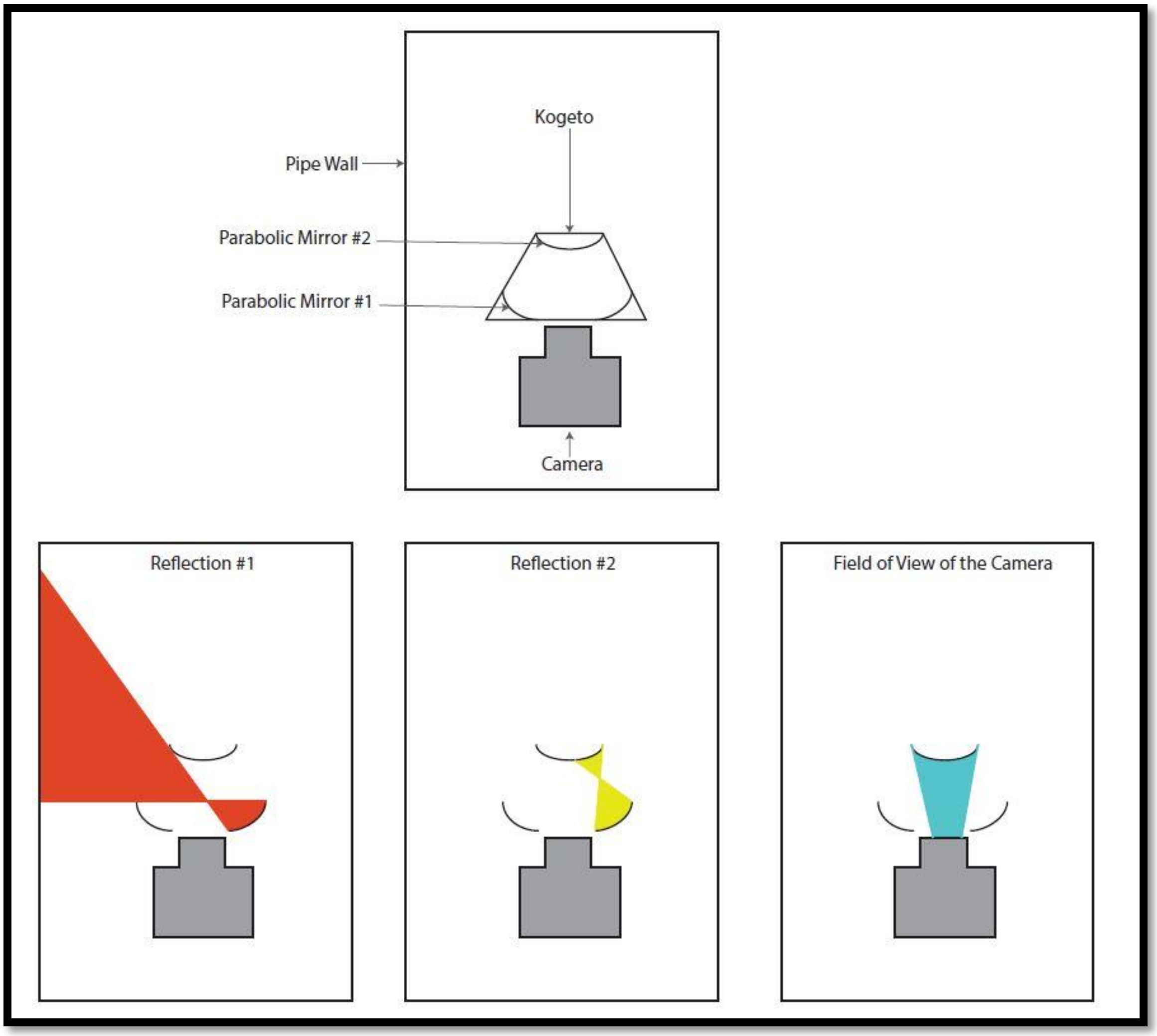


Figure 53 - Kogeto ODVS cross section and reflective path

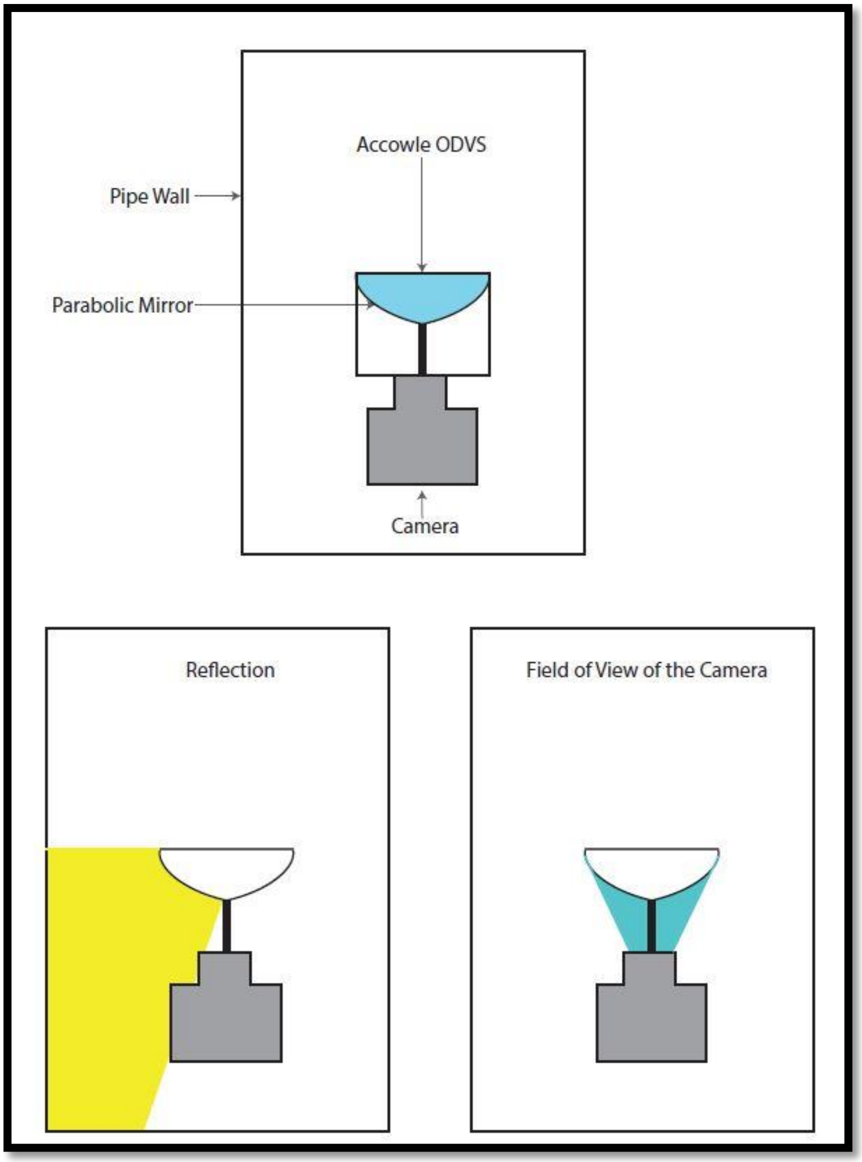


Figure 54 - Accowle ODVS cross section and reflective path

The Kogeto ODVS is designed to be used with the iPhone but it can be used with any similar camera. For a proof of concept the Kogeto was mounted to an analog camera (low resolution) and the Leopard Imaging HD Camera (Figure 55). The Accowle ODVS is designed to work with the Basler GiG E Camera (Figure 56).

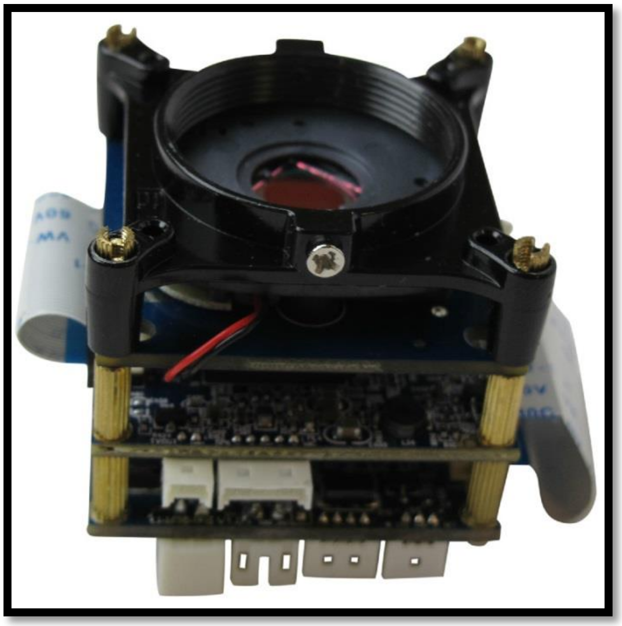


Figure 55 - Leopard Imaging HD camera

Figure 56 - Basler GiG E camera

Five cameras were tested, an analog camera (Figure 57) with a resolution of 420 x 780, the iPhone camera (Figure 59) with a resolution of 1920 x1080, The Sony Bloggie with its own ODVS (Figure 58) with a resolution of 1920 x1080, the leopard imaging HD camera with the Kogeto ODVS (Figure 60) with a resolution of 1920 x 1080, and the Basler Gig E camera with the Accowle ODVS (Figure 61) 1280 x 1024.

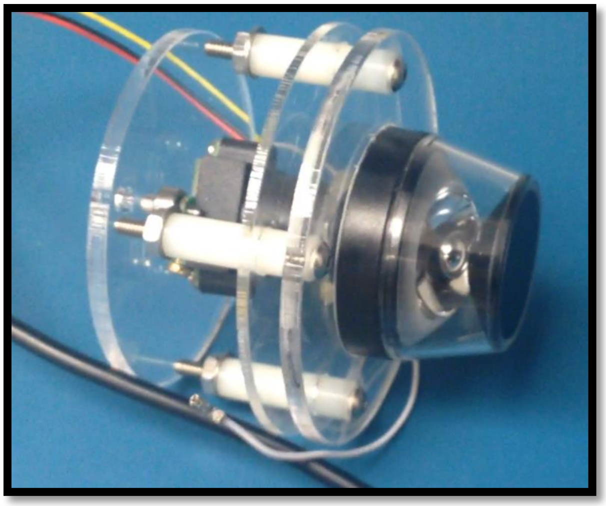


Figure 57 - Kogeto mounted to analog camera

Figure 58 - Sony Bloggie with custom ODVS

Figure 59 - Kogeto mounted to iPhone

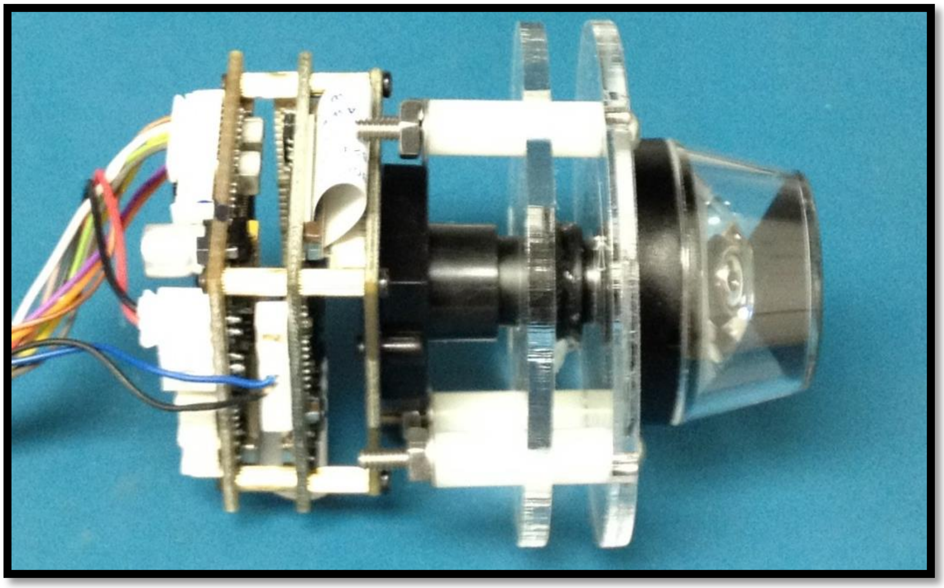


Figure 60 - Kogeto mounted to Leopard Imaging HD camera

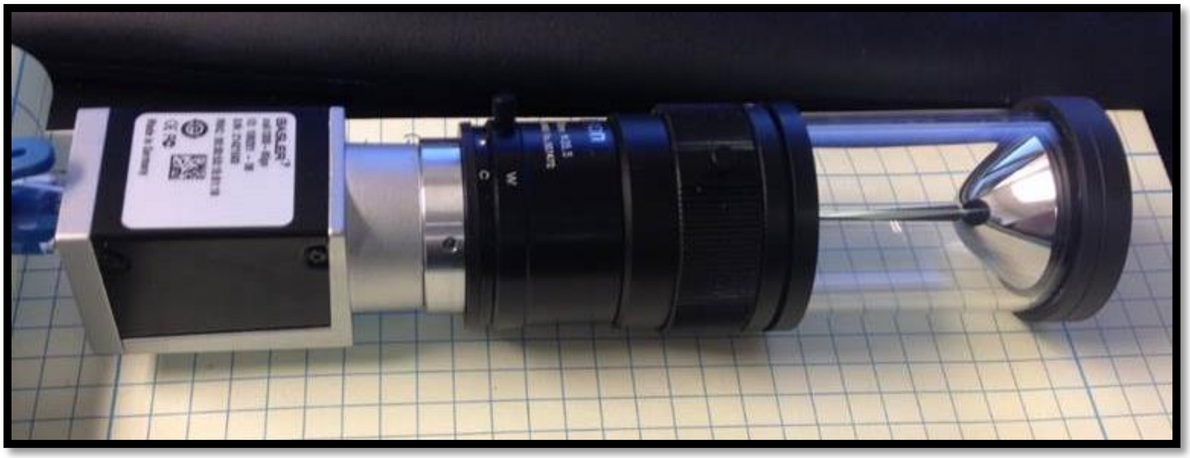


Figure 61 - Accowle ODVS mounted to Basler Gig E camera

All cameras and their respective ODVS's performed optimally (with the exception of the analog camera) an example of the results can be seen in Figure 62 and Figure 63.

Figure 62 - Leopard Imaging HD camera pipe test (letters)

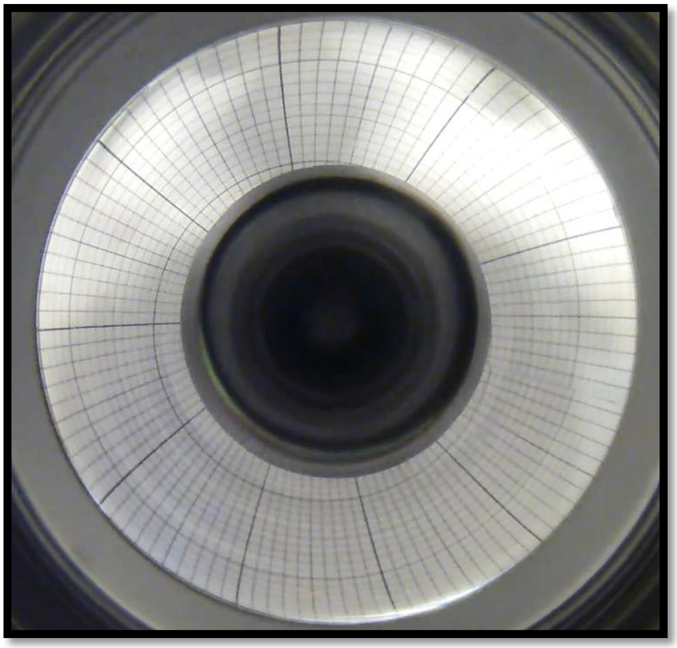


Figure 63 - Leopard Imaging HD camera pipe test (graph paper)

Vision Labview Program

Preliminary LabVIEW vision program development was conducted. In order to perform a proof of concept the built in computer webcam in the Lenovo W530 ThinkPad was used along with a 3 axis accelerometer which was attached to the rear of the laptop. The accelerometer, as seen in Figure 64, was included in order to determine the orientation of the robot since there is a possibility of rolling during inspection.

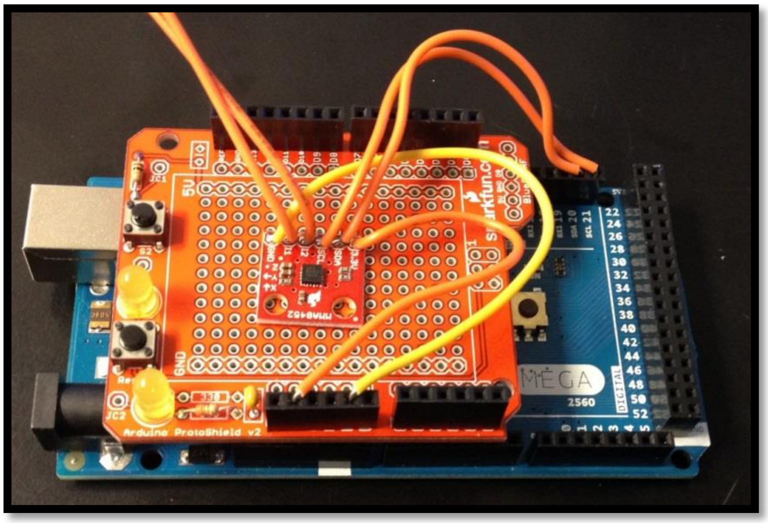


Figure 64 - Accelerometer connected to Arduino micro controller

A test was constructed where grid paper was placed within the field of view of the webcam to check the program as seen in Figure 65 and Figure 66.

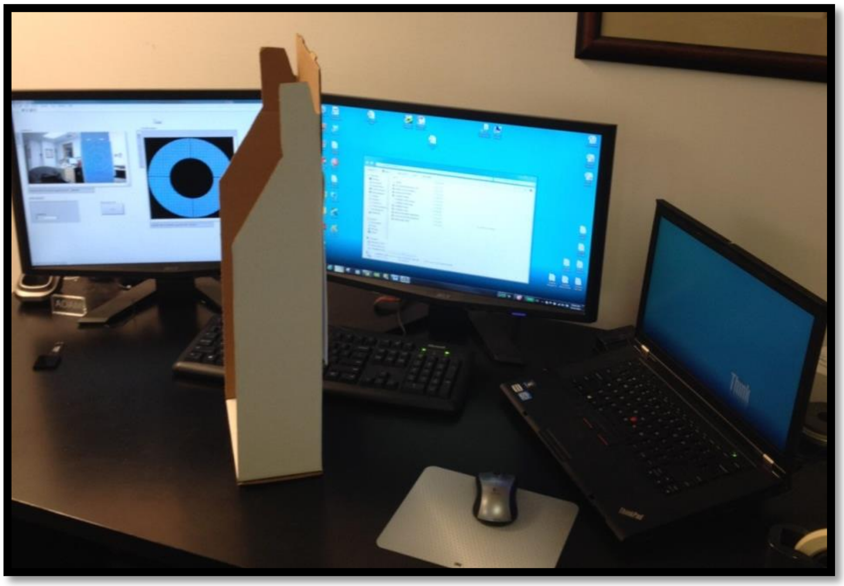


Figure 65 - LabVIEW grid test view 1 (vision system)

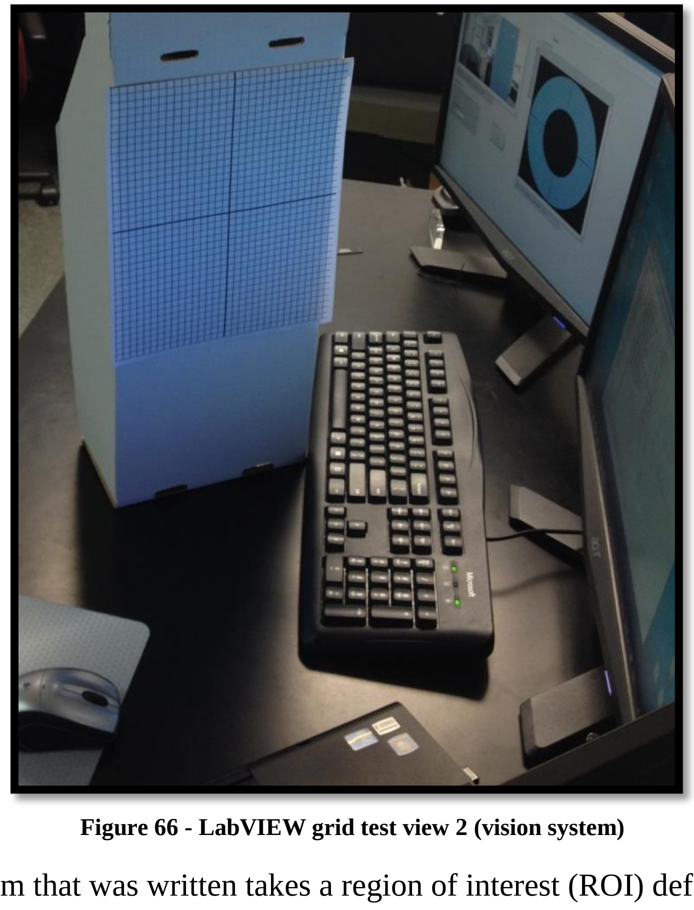


Figure 66 - LabVIEW grid test view 2 (vision system)

The labVIEW program that was written takes a region of interest (ROI) defined by the user and masks the rest of the video (Figure 67).

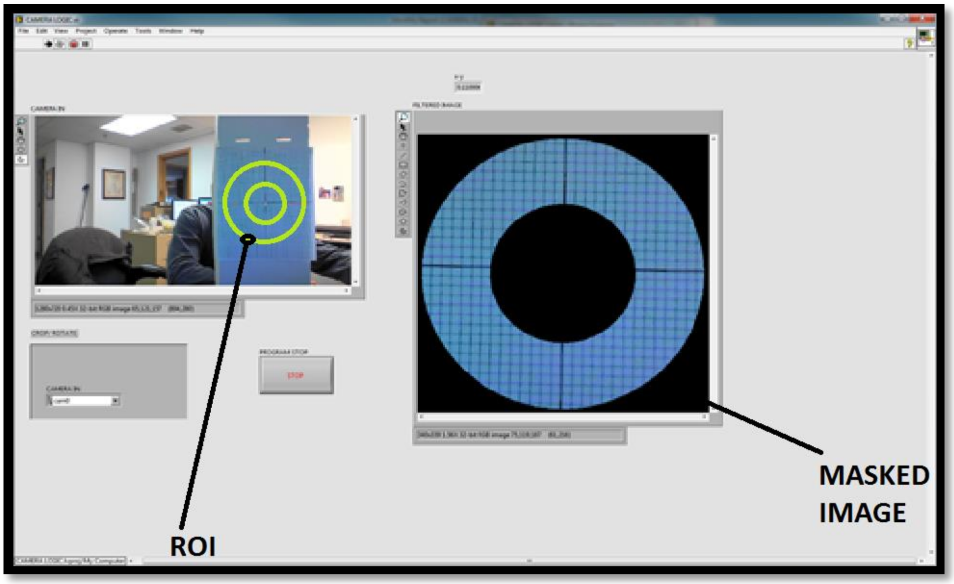


Figure 67 - LabVIEW front panel (vision system)

If the computer is tilted at all the Arduino sends the serial accelerometer data to LabVIEW. From there the data is goes through a low pass filter. The angle is then used to rotate the masked image so the invert of the pipe will always be on the bottom of the screen as seen in Figure 68 and Figure 69.

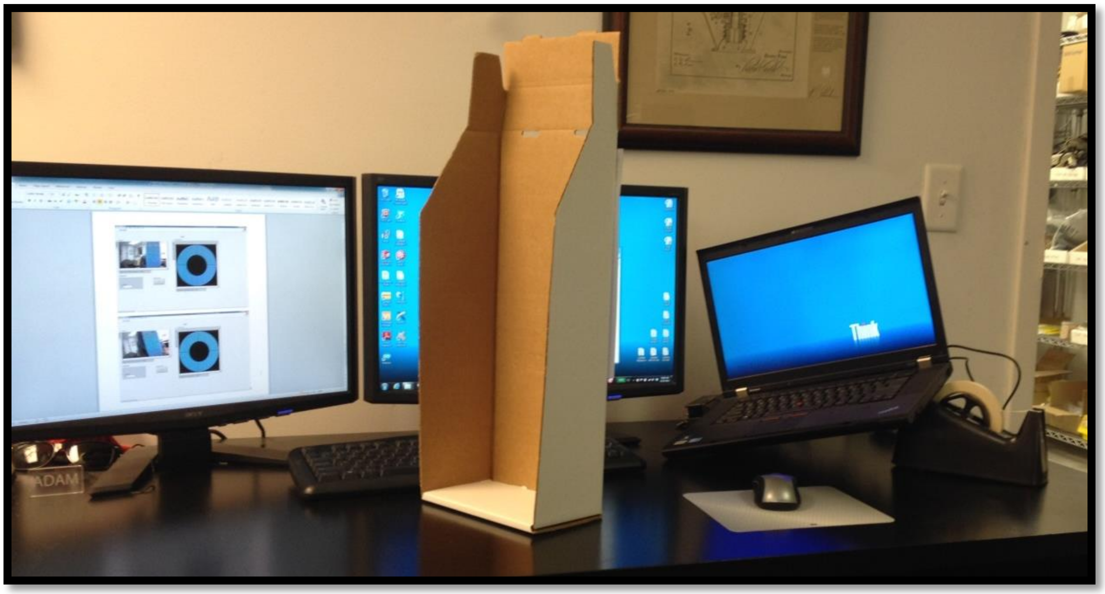
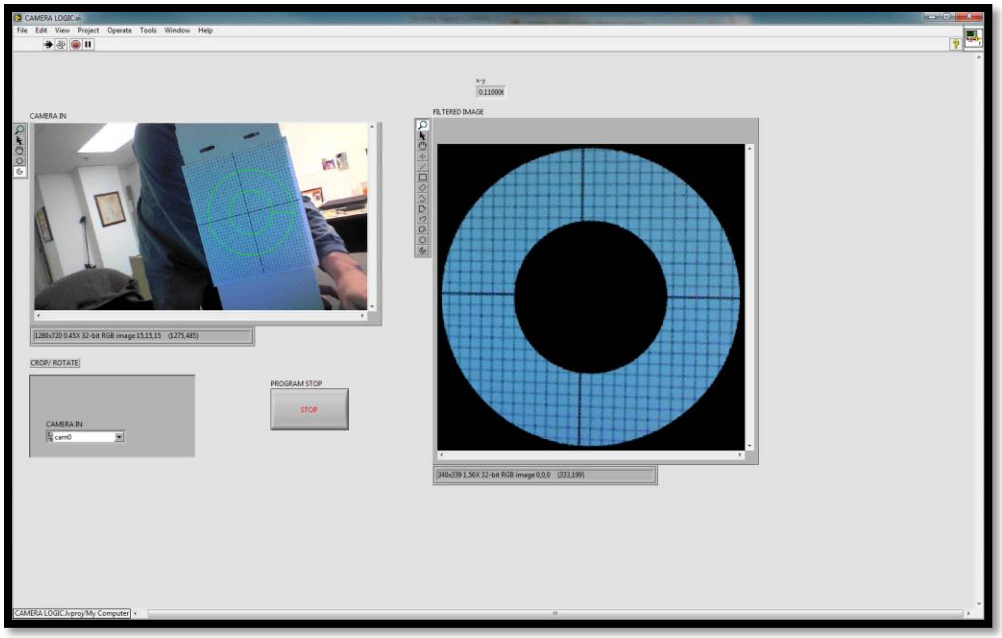


Figure 68 - Tilted computer test



x-y: 0.11000

1280x720 0.45X 32-bit RGB image 15,15,15 (1275,485)

CAMERA IN: cam0

340x339 1.56X 32-bit RGB image 0,0,0 (333,199)

Figure 69 - Tilted computer test LabVIEW front panel

Future Work

To this point, robot development has generally been concerned with identifying and implementing proof of concept techniques for in pipe locomotion and navigation. Future work will center on building a robust, reliable robot based on the techniques learned in this phase.

Future work to develop a functional prototype will include:

- Design and build application capable designs investigated in Ph1.
    - Design/modify and build robust gripper module.
    - Design/modify and build robust flexible pneumatic cylinder.
    - Design/modify and build steering head.
    - Design/modify and build circular camera system.
    - Design/modify and build TCP based control system.
- Design and build robot tether.
    - Investigate and implement high bandwidth data connection for streaming high definition video.
    - Investigate and implement pneumatic and electrical supply methods.
    - Investigate and implement low friction jacket material for ease of travel through pipe.
- Design and build robust electronic control system.
    - Develop a modular electrical system, in which each module is connected via an addressable bus system.
    - Implement deterministic control of the robot, as opposed to the current time based control.
    - Design and build small, form factor optimized printed circuit board assemblies.
- Test robot in mock piping scenarios.
    - Build piping system which is representative of the piping typically encountered in fleet piping systems.
    - Test robot in a variety of piping scenarios.
- Design and build operator control station.
    - Design and build a small, robust station capable of being used in the tight locations typical of fleet engineering spaces.
    - Develop a system to allow easy control of the robot, while displaying acquired information in a simple, concise manner.
    - Implement an electrical power source, using ship 120VAC.
    - Implement a miniature compressed air source, using ship 120VAC.

Conclusion

Electromechanica has researched, developed and designed a prototype proof of concept robot, showing that internal navigation of 3in internal diameter piping is possible. Various techniques and methods were investigated for robot control, locomotion and navigation. Future work is required to develop a fully operational prototype, to be used for the in-situ inspection of fleet piping.

Financial

Project Total	$149,902					
Month	1	2	3	4	5	6
Period	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14
Milestone Payment	$ 26,000.00	$ 26,000.00	$ 26,000.00	$ 26,000.00	$ 26,000.00	$ 19,902.00
Payment Total Cumulative	$ 26,000.00	$ 52,000.00	$ 78,000.00	$ 104,000.00	$ 130,000.00	$ 149,902.00
% Project Total Cumulative	17%	35%	52%	69%	87%	100%
Invoiced	Yes	Yes	Yes	Yes	Yes	Yes
Received	Yes	Yes	Yes	Yes	Yes	No