Flight Telerobotic Servicer

by

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BEng, University of Victoria, 2003

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of the Requirements for the Degree of
MASTERS OF APPLIED SCIENCE

In the
Department of Mechanical Engineering

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Supervisory Committee

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Abstract

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In 2010, a donation was given to the University of Victoria Robotics and Mechanisms lab by Roper Industries. It was a Flight Telerobotic Servicer (FTS) Right Finger training tool. This is an electro-hydraulic robotic arm, approximately eight feet long, weighing in excess of four hundred pounds. This arm was designed and built in the late nineteen eighties as part of a program in support of the Space Station Freedom project. The intention of the arm was to assist in the training of astronauts in the use of an end effector which would be mounted at the distal end of the Canadarm©. The end effector would have right and left fingers, as well as a thumb (used for stabilization, not grasping).

Unfortunately, the robot did not come with any of the control hardware, software, manuals, or functional descriptions, and the original equipment manufacturers (OEMs) were not able to share any information regarding the nature of the controls.

The focus of the present work is to re-animate this arm without additional feedback, operating the arm only by hand-eye control, using currently available electronics and hardware. Also, investigate the absolute position sensors. These are described as near-infinite resolution analog absolute position sensors. Investigation was also conducted on an alternate solution (Vernier Optical Encoder), which was finally were abandoned. Strain-gauge type torque feedback sensors were found to be functional, and can be used without further work on future experimentation.

The outcome of the research and assembly is a fully functional electro-hydraulic robotic arm, which is digitally controlled using an XBOX© game controller, using only visual feedback for position. The position sensor work was not as fruitful, with no working position sensors available. The torque feedback sensors are functional, but not utilized in the final work.
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Acronyms

FTS – Flight Telerobotic Servicer
DOF – Degrees of Freedom
ISS – International Space Station
RAM - Robotics and Mechanisms
WSM - Western Space and Marine
PSI – Pounds per Square Inch
GPM – Gallons per Minute
HMI - Human Machine Interface
HID - Human Interface Device
EE – End Effector
PWM – Pulse Width Modulation
VOE - Vernier Optical Encoder
AC – Alternating Current
DC – Direct Current
CPR – Cycles Per Revolution
1. Chapter 1: Introduction to the Flight Telerobotic Servicer

1.1 Introduction and Background

Humans in space… It is a dream shared by every person staring into the night sky. However, there are challenges with getting there, with staying there. In order to inhabit outer space, first a structure is required to live in. A permanent structure, large enough to inhabit for weeks or months at a time, is too large to lift out of the earth’s gravity in a single piece. Therefore, it must be assembled in space, from smaller sections carried up into orbit on the space shuttle or other ferrying rockets. In order to assemble sections in space, two pieces must be brought together and fastened, to become an assembly. On earth, this is a commonplace activity,
using cranes or lifting/manipulating equipment, or manually by hand with smaller pieces. However, in orbit, there are no cranes, and access to do manual work is both limited and dangerous.

Enter the Canadarm®, a manipulator mounted to the space shuttle, used to maneuver large pieces in orbit. This arm is used to launch large pieces from the shuttle payload bay as well as capture and control pieces already in orbit, that require some form of intervention. Unfortunately the Canadarm has a single gripper end effector, so it is not possible to grasp more than one article at a time. In order to do assembly work, two independent manipulators are required. An anchoring system is also required, in order to have a relatively stationary origin for the work.

The original Flight Telerobotic Servicer (FTS), as designed by Martin-Marietta, was intended to address all of these requirements. It has two independently controlled manipulators, as well as an anchoring system (see Figure 1-1). Each of the manipulators has seven independent rotary joints, and the anchor has five rotary joints. The complex movements available with these three appendages are staggering, and would be difficult for even an experienced operator to control.

The arm was equipped for force and torque feedback, as well as position feedback, required for remote operation. Each arm was intended to have a precision of 1.0 inches in position and 3.0 degrees in orientation [1].

The FTS was developed as a training model, to ensure that the astronauts that would be using the FTS had ample time to get used to all of the functions of the system prior to actual use in space. The FTS robotic arm that is currently in the University of Victoria Robotics and Mechanisms (RAM) lab is the actual training tool manufactured to assist in training astronauts [2]. It was used at the NASA Test Site, presumably at the Martin Marietta Astronautics Group, in
Denver, Colorado. This electro-hydraulic arm allows the astronaut to train on earth, in preparation for space-based activities. The interface would be the same as that planned for the flight robot, and could even be the actual interface used for space flight.

1.2 History of FTS

The FTS is a multi-armed robot, as seen in Figure 1-1, was designed to assist in the construction and maintenance of the Space Station FREEDOM. The assembly consisted of two identical (mirrored) seven degree of freedom (DOF) arms for manipulation, and a five DOF arm used as an anchor for stability and positioning. The body of the manipulator would house the control mechanisms, power supply, and end effector tools.

The FTS was intended to be operated by an astronaut either in orbit or on earth, using remote control and positioning cameras. The intent was to develop the ability to have some autonomous ability as well. The FTS would be anchored to a fixed point, such as a portion of the space station, with the five-DOF arm, while the two seven-DOF arms manipulated two payloads, either to assemble them together, or as separate objects altogether. This system would give an astronaut a robust system for assembling a space station, or making repairs to a satellite.

The Space Station FREEDOM Program began to lose funding in the late nineteen eighties. By nineteen ninety three [3], the program had been reconfigured and amalgamated with the ESA and the MIR-2 program, to become the International Space Station (ISS). The assembly of the ISS was less complicated, and the need for a dextrous manipulator had diminished. This was the end of the FTS program.
One of the FTS Training Arms, as seen in Figure 1-2, was purchased by Roper Industries, and subsequently donated to the Robotics and Mechanisms (RAM) Lab. The arm was designed as a training robot to assist astronauts who would build the Space Station FREEDOM. It was manufactured and operated in California, at Western Space and Marine (WSM), in 1989. This electro-hydraulic arm was designed as a training arm only, never intended for flight. It was assembled and operated at WSM before being placed in storage. General dimensions can be seen in Figure 1-3.
1.3 Original Components

Each of the seven joints has a hydraulic supply and return line, hydraulic actuator, hydraulic servo valve, a pressure sensor, a high precision encoder, and a force detection system.

The actuator size and shape vary over the length of the arm, depending on force required and amount of rotation required. The shoulder joints are the largest, each with four hydraulic cylinders acting on two rack and pinion assemblies, allowing for ~one hundred eighty degree rotation, while the wrist has four smaller hydraulic cylinders operating a pinion to rotate more than three hundred sixty degrees.

The hydraulic servo control valve (See Figure 1-4) is manufactured by Moog, and literature for it is readily available. This control valve will operate in proportion to a current that
is applied to it. Polarity of current dictates whether the valve will allow the actuator to extend or retract. There are seven of these valves on the arm. Current is applied to the valve through a servo amplifier, typically at +/-5 volts.

The pressure sensor is used to calculate force applied by the arm. The pressure sensor force feedback equation is unique for each position, utilizing the arm kinematics, cylinder dimension, rack and pinion dimension information, etc. to calculate actual force and moment information. The pressure sensors on the arm are custom units, with no vendor information available. These will require calibration once the arm is operational.

The high precision encoder is of unknown design, expected to require an input frequency to obtain a frequency output that would relate to a quadrant position. However, without knowing the input frequency or the expected output, these encoders are of little value to this project.
The torque sensors are hidden deep inside each of the joints. These are functional, used during lab trials. There is an operational amplifier and power supply for each of the strain gauge-style sensors, one set inside the shoulder, and the other inside the lower arm.

The hydraulic system for the FTS was designed for three thousand pounds per square inch (psi) of pressure at up to twenty gallons per minute (gpm) flow rate. This system has a common header for pump supply, and another common header for tank return. This hydraulic pump would likely be variable displacement, maintaining three thousand psi at the header, regardless of flow rate.

1.4 Project Objectives

The FTS arm was originally analog controlled, with absolute position feedback, torque feedback, hydraulic pressure feedback, and position control. It is a 7-R robot, which means that it has 7 rotary joints, interpreted as a pseudo-spherical shoulder (3 joints), an elbow joint, and a pseudo-spherical wrist (3 joints). The pseudo-spherical joints, both shoulder and wrist, each have three orthogonal joints to create the assembly. They are not truly spherical, as the three joint axes do not intersect at a common point.

Unfortunately, the robot did not come with any of the control hardware, software, manuals, or functional descriptions, and the original equipment manufacturers (OEMs) were not able to share any information regarding the nature of the controls.

The focus of the present work is to:

- Re-animate this arm without additional feedback, operating the arm only by hand-eye control, using currently available electronics and hardware. The control of the arm is designed utilizing LabVIEW 2010© installed in a Panasonic© CF-F9 laptop computer, a
LabJACK U3-HV© Data Acquisition device, an XBOX © game controller, as well as several motor controller chips and prototyping breadboards, LEDs, etc.

- Investigate the absolute position sensors. These are described as near-infinite resolution analog absolute position sensors. There are no known methods to animate these sensors. Alternate digital solutions (Vernier Optical Encoder) were attempted, but finally were abandoned.

- Investigate and utilize the strain-gauge type torque feedback sensors. The torque feedback sensors were successfully operated, though not included in the final presentation. These were found functional during trials for the optical encoder.

During this project, the sensors were investigated, with the torque feedback operational, the pressure feedback unknown, and the position feedback non-operational. The control valves were investigated, found to be viable, so an operating system was created in order to verify the operability of these valves.

The operating system consisted of a hydraulic pump with isolation valve, hoses, and filter; Cabling junction and identification systems with multiple LEDs for identification and continuity confirmation; an interface board complete with valve controllers and power supply; a LabJACK controller interfaced with a computer, LabVIEW software to control the arm, and an Xbox controller, as the Human Interface Device. All of this equipment, connected to the arm, allowed for full control of each of the joints.

The outcome of the research and assembly is a fully functional electro-hydraulic robotic arm, which is digitally controlled using an XBOX© game controller, using only visual feedback for position. The position sensor work was not as fruitful, with no working position sensors available. It is the goal of this project to have an operational arm which can be used as the basis for further study and experimentation.
Chapter 2: Design Objectives and Methodology

2.1 Mount the Arm

![Diagram of the FTS Robotic Arm]

The arm came with a stand and has a known work envelope (see Figure 2-1). This stand will require mounting in a location where the arm could make full use of this work envelope.

The stand was originally mounted against the exterior wall in the south portion of the RAM lab, but as the space was reallocated, the stand must be moved to a location along the north interior wall, adjacent to the exit door. This is not an ideal location, but with some care, the arm can still use most of the work envelope.
2.2 Develop a Control Strategy and System

The control and operation system will be electro-hydraulic based. It will consist of a hydraulic pump with a reservoir, isolation valve, servo valves, hoses, and a filter. The existing controller that shipped with the arm was found to be incomplete, obsolete, and non-serviceable, so it will be abandoned in favor of modern equipment. A new control strategy is proposed in this thesis, which consists of a new cabling junction and identification systems with multiple LEDs for identification and continuity confirmation; an interface board complete with valve controller chips and a power supply; a LabJACK controller interfaced with a computer, and an Xbox controller as the Human Interface Device (HID). All of this equipment, connected to the arm, will allow for full control of each of the joints.

The parts for this operating system will be chosen based on two criteria: Fit for Purpose; Cost Effective. First and foremost, the parts must be able to perform the required task, at some level. It may not be able to perform as OEM parts, but at least enough to prove the concepts. Second, the cost of the components must be reasonable. This is an unfunded project, so all expenses are covered by the author (perhaps not a typical starving student, but nonetheless unfunded). Almost all of the materials purchased for this research will remain in the control cabinet as part of the final product.

2.3 Animate the Arm

The primary goal of this research is to animate the arm. Apply hydraulic pressure to the system, actuate a valve, and observe a predictable response in the arm itself. Having the arm functional after so many years in storage is not a reasonable expectation, but it is easier to detect flaws once the system is operational.
Using an Xbox controller to manipulate the arm is both cost effective and familiar. A large percentage of the audience is familiar with this interface. Deciding on the intimate detail of the interface will be based on the experience of the author as a heavy equipment operator. Heavy equipment will typically have a common interface, so that as the operator changes from one piece of equipment to another, there is a minimal learning curve to operate the different machines. For example, on the arm, the left joystick, when moved left or right, will control the second (swing) shoulder joint, similar to that of an excavator. The right joystick, forward – back motion, will control the curl of the elbow joint, also similar to an excavator. Other functions will be similarly organized. This is interchangeable with any other controller input, by exchanging wires on the valve control board, or, with more difficulty, on the FTS interface board, or programmatically.

2.4 Investigate the Sensors

There are three sensing systems on each joint of the arm; a torque feedback sensor, a hydraulic pressure sensor, and a position sensor. These sensors are utilized to know where the arm is and what it is doing. For remote operation, these sensors will provide enough feedback to adequately operate the arm without causing harm to the equipment being manipulated, as well as knowing where the pieces are being moved from and to.

The torque sensors were found to be operational, the pressure feedback sensors were not investigated, and the position sensors were investigated extensively, with no success. Alternate solutions were attempted for the position sensors, such as a Vernier Optical Encoder design that had great promise, but ultimately did not result in a successful product.
Chapter 3: Mechanical System Description

3.1 Mounting Stand and Arm

The arm, manufactured by Western Space and Marine, shown in Figure 3-1, is mounted to the left of the main entry to the Robotics and Mechanisms (RAM) lab, EOW 121. The stand is attached to the floor with twelve Hilti© Kwik bolts© [4], each with a pull-out strength of more...
than two thousand pounds force. Assuming that the arm is eight feet long and four hundred pounds, evenly dispersed, and can lift an additional two hundred pounds at the end effector, then the moment applied to the stand could be up to sixteen hundred foot-pounds for the weight of the arm, plus an additional sixteen hundred foot pounds of payload, for a total of thirty two hundred foot pounds. The stand, with a minimum of four bolts always in reaction to this moment, at an average distance of three feet away, with two thousand pounds of resisting force possible for each bolt, could react with twenty four thousand foot-pounds of torque, or a safety factor of more than seven. Of course, there are generalities in the equation as stated above, but it is an illustration that the stand is mounted in such a way as to be well over-built, and is not to be a safety concern moving forward.

The arm itself is generally made of machined 7075 aluminum [5], with steel gears, hydraulic pistons, shafts and bearings. The arm was not disassembled more than enough to gain access to a hydraulic leak or some of the electronics. When originally assessed, it was found on a pallet, under several layers of wiring harnesses and miscellaneous bits. In order to mount the arm, it needed to be lifted up about three feet and inserted onto two dowels on the stand, and then bolted while being supported. As the arm is about four hundred pounds, and each joint was free moving, there were too many pinch points to try to perform this task manually. An engine hoist was used to lift the arm onto the stand, ensuring that there were no injuries or damaged components during assembly. Once mounted, the arm flexed down and across the floor, where it lay during much of the research period.
3.2 Hydraulic System

3.2.1 Overview

The hydraulic system on the arm was not tampered with, aside from replacing several leaking seals. Therefore, cylinder sizes and stroke were never measured, and potential forces were never calculated. It has been proven that the original design is adequate to move the arm alone, and with a higher pressure and flow pump, a load could also be carried by the arm. There is a control valve on the wrist that passes hydraulic fluid, and this allows the joint to constantly creep. There is also a leak, believed to be originating in the wrist pressure sensor, which is difficult to identify. It is still leaking occasionally, out onto the floor.

3.2.2 Hydraulic Pump

The FTS system did not have a pump when it was donated to the University of Victoria. There was no indication of the pump requirements for this arm, only the capacities that each of the valves was capable of handling, and the line sizes. The limiting factors for new pump specification were twofold; First, there is limited AC power in the RAM Lab. Availability is less than fifteen amps at one hundred ten volts (i.e. typical household power receptacle). Second, the budget for the pump is limited to less than a thousand dollars. This pump was supplied by the author, as this is an unfunded research effort.
The chosen pump (see Figure 3-2) is capable of only .3 gpm maximum flow, and .2 gpm at 3000 psi rated pressure, and was the largest available for the supplied power. The original pump, based on actual operation of the arm, could have been 10-20 gpm at 3000 psi and would not have been too large. The smaller pump is able to accommodate the power availability and financial concerns, and prove the function of the arm.

The FTS hydraulic system is not a loop system, but rather has twin headers, supply and return. This type of design would typically utilize a variable displacement pump or a fixed displacement pump with accumulator tank and pressure switch for pump control. The pump installed is a fixed displacement pump without pressure control. Therefore, it is constantly passing fluid across the internal pressure relief valve, operating at full pressure and flow at all times. This is less than efficient, but it is within the constraints of the design and budget. In order to reduce the time the pump is working at this maximum work point, a control valve is fitted to the pump to bypass the arm, controlled by a switch on the control cabinet door. The arm is bypassed on initial start of the pump, as well as when the pump is shut down. This helps to close in the system when it is shut down and reduce wear on the relief valve.
3.2.3 Hydraulic Piping

The hydraulic piping system on the FTS Robotic arm includes a combination of stainless steel tubing and machined (and sometimes anodized) aluminum. The pump supply port on the shoulder is one quarter inch diameter (nominal), with a designation of -4-, which indicates a size of 4/16 inches. The tank return line is -6- (6/16”). These lines traverse the arm, swiveling through each of the joints, dead-heading at the third (last) wrist joint. The seals for the piping and swivels are generally O-rings for fixed connections, and a combination of seals with a rectangular cross section and O-ring back-up seals. Connections between the piping and machined aluminum components are typically a Swagelok© threaded compression-type connection.

Between the arm and the pump, there are flexible hydraulic hoses, with a filter between the return line from the arm and the reservoir tank. This is in place to ensure that any foreign material dislodged from the hydraulic system does not contaminate the tank.

3.2.4 Hydraulic Actuators

There are eight hydraulic actuator assemblies on the FTS robotic arm. Each joint has a combination of four pushing cylinders, situated as opposing pairs (See Figure 3-3 arrows). There is a pinion centered on the axis of each joint, and a rack between each of the opposing cylinders, acting on the pinion. The torque required to rotate the arm about any particular joint is generated by applying hydraulic pressure to diagonally-opposed cylinders. This generates a force of two times the applied pressure times the cylinder area, applied to the pinion from opposite sides, but in the same sense. This force, multiplied by the effective radius of the pinion gear, translates into a torque.
Each of the joints is constructed in a similar fashion, with the diameter of the cylinders being reduced for each consecutive joint, up to the seventh joint. The final joint has two semi-independent cylinder sets (see Figure 3-4 arrows), joined by a common pinion. This allows for three hundred sixty degrees of rotation of the end effector (EE).
3.2.5 Hydraulic Servo Valves

Each of the actuators has a servo valve to control it. Each valve is a four port, three position servo valve, with closed centers (see Figure 3-5 for basic schematic).
The servo valve is a proportional valve, reacting according to the current applied to a pair of coils inside (see Figure 3-6, courtesy of Moog [7]). The electromagnetic force inside the valve is balanced by the mechanical feedback, making it possible to do so. The flow through this type of valve is proportional to the amount of current applied to the coils. Direction is also dictated by current direction. This can be treated in the same fashion as a permanent magnet DC motor. Applying a minimum of current to the valve may not overcome internal frictions, similar to a DC motor. In similar fashion, to overcome this friction, dither can be applied. This is applied as a
pulse width modulation (PWM) to the coil. This is a simple method to vary the current across the coils as well as ensure that the friction is overcome.

A general purpose (on-off) hydraulic valve is typically on or off, with no partial opening. These are also not conducive to pulse width modulation, as they are very slow acting. If speed control is required for actuation, an on-off valve is not the best choice. If there is no alternative, then it is possible to combine an on-off valve with a hydraulic flow diverter-controller. The control valve mounted directly to the pump is an on-off valve.

With the low flow of the chosen pump, there was no requirement for a PWM control system. One was applied during initial trials, but it was found that the valves were always open fully, so the PWM configuration was removed. Once a more robust, higher volume pumping system is installed, PWM would once again be required.

3.2.6 Pressure Feedback Sensors

There is a pressure sensor attached to the piping of each actuator (see Figure 3-7), mounted adjacent to each control valve. Each pressure sensor has two ports, one for each side of the actuator. This allows the pressure sensor to sense the pressure applied to each side, so the sum can be used to help calculate the torque applied to each joint. This also makes it possible to kinematically calculate the force at the distal end of each arm segment, and therefore the force applied at the end effector.
The pressure sensors were not active during the bulk of the experimentation, as there was no pressure available to sense. The sensor system looks to be a simple strain gauge and Wheatstone bridge arrangement, applying a constant voltage to one side and measuring the voltage on the opposite side, and using that voltage to calculate an applied pressure. No further investigation was done with these sensors.
Chapter 4: Electronic System Description

4.1 Torque Feedback

There is an analog Torque feedback sensor at each joint. These are strain-gauge based sensors, with the Wheatstone bridge arrangement located in one of two circuit boxes, one found in the shoulder, and one found in the forearm. These were used during experimentation with the arm, as the original information on them was that they were analog position sensors. On investigation, it was found that they are used to sense the strain at each of the joints, and can therefore be used in a similar manner to the pressure sensors mentioned earlier, in section 3.2.6. The strain gauges are mounted deep inside the joint, on the pinion shaft of each joint.

![Strain Gauge mounted under protective sleeve](image-url)
The strain gauge is attached to the pinion shaft shown in Figure 4-1, with the connecting wire wrapped around the shaft to allow rotary motion. This particular joint has a double actuator system, acting on each end of the pinion shaft, to increase the range of the joint.

Figure 4-2 Sketch of original circuit board for torque sensors, illustrating major components (the red box is around 1 of 3 Wheatstone Bridge – Op-Amp arrangements)

Note: this is original equipment, and specifications are not known
The strain gauge is attached to the Wheatstone bridge circuit (Figure 4-2, red box), and a variable voltage is returned on the output of the operational amplifier (see Figure 4-3), dependent on the torque applied to the joint. This torque can be kinematically accumulated into a force applied to the end effector, in a similar manner to the pressure sensors. Having some redundancy in the force sensing system is important for this type of arm, as the intention is to operate this arm remotely, and have as much information as possible about the reactive forces on the arm.

There are 3 circuit boards for the arm. One is in the shoulder, and two are in the fore-arm. The blue is printed on one side of the board, and the white is printed on the other. \( R_1 = R_4 = 5 \text{k}\Omega \), and all the other resistors are \( 256 \text{k}\Omega \). Capacitors \( C_1 = C_2 = .1\mu\text{F} \).

4.2 Absolute Position Feedback

Each joint on the arm has an analog absolute position sensor. Each sensor is identical in size and function (See Figure 4-4).
After many hours of research and interviews, there was very little accomplished towards having these operational. There are several integrated circuits, as well as some overlapping coils; half stationary, half rotating with the joint (see Figure 4-5). The assumption is that if a frequency is applied to the rotating coil, the stationary coil would have a frequency applied to it, and would
return a signal that was related to the position, giving the opportunity to achieve absolute position.

The physical sensor on each joint has a hollow center, for the hydraulic lines to pass through. This is a challenging constraint when attempting to replace the sensor with a modern stock design. There are hollow-center sensors available, but all that were identified were not the correct accuracy, size or shape, or not in the appropriate price range.

Chapter 5: Design of an Absolute Position Sensor

5.1 Design Requirements

The design of a new absolute position encoder was done for use with the arm. Due to the problems with the original encoder (as explained in 4.2), a new design was undertaken. This new encoder has some strict design requirements including absolute position sensing, high-resolution, tight workspace volume, and limited resources in the available data acquisition system for data signals. A variation of an optical encoder was developed using the theory behind
a Vernier Caliper, using two slotted, concentric rings, with the outer ring having one more slot than the inner ring. The criteria used for designing this new sensor are described in Table 5-1.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Design Requirement(s)</th>
<th>Constraint(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (Absolute or Relative)</td>
<td>Absolute</td>
<td>No 'Homing' required for Initial position.</td>
</tr>
<tr>
<td>Accuracy (Degrees, Inches)</td>
<td>3 degrees of precision, and 1 inch of accuracy at end effector</td>
<td>To meet original design criteria.</td>
</tr>
<tr>
<td>Physical Shape</td>
<td>Fit in original equipment envelope. Have a hollow center.</td>
<td>Mechanical design of arm will only allow this configuration.</td>
</tr>
<tr>
<td>I/O required</td>
<td>2 lines of I/O maximum.</td>
<td>The arm has 7 joints, and more than 2 I/O lines would require more than one LabJACK, which only has 20 digital I/O ports.</td>
</tr>
</tbody>
</table>

Table 5-1 Alternate Position Sensor Design Requirements/ Constraints

5.2 Phase Shift

The intention was to create a sine wave for each of the two slotted rings, as the slot passes in between an LED emitter and a photodiode. The photodiode voltage would rise and fall according to the location of the slot, giving excellent resolution over one or two degrees of rotation [8]. Comparing two sine waves, and the phase shift between the two sine waves, could offer the absolute position of the sensor. The encoder ring that was being experimented with had one hundred eighty slots on the major ring, and one hundred seventy nine slots on the minor ring (See Figure 5-1).
Initial results warranted further investigation (See Figure 5-2). As one looks at the peaks on the yellow and the red curves, it can be noticed that there is a difference in ‘frequency’, which is the basis for the works. Please note that the ‘frequency’ is not time based (Hertz), but rather rotation based, with a unit of cycles per revolution (CPR), and that the major ring, represented in red in Figure 5-2, represents 180 CPR, and that the yellow represents 179 CPR.

In this initial data, the X- and Y-axis are showing a raw scale of voltage. The X-axis is the voltage of a potentiometer, rotating directly with the slotted wheel, used as an absolute reference. The Y-axis is the voltage developed in the photodiodes for each of the major and minor slotted rings. The maximum voltage values from the photodiodes can be adjusted using resistors, so the maximum and minimum values from both photodiodes can be equalized (See Figure 5-6).
5.3 Refined Models

There were some issues identified with preliminary data, so several test jigs were assembled, in order to eliminate tramp light as well as limit the width of the LED light. Blinds were machined for the LED and Photodiode pairs. This would help limit the emitted light to a single slot width, as well as limit the detected light to a single slot width. All of the improvements (See Figure 5-3, Figure 5-4 and Figure 5-5) were useful to create a cleaner sine wave. For precision of a point within a one-degree range, this works well.
Figure 5-3 Final Version of the Vernier Optical Encoder

Figure 5-4 LED Holder and Mask Arrangement
LED Holder and Photodiode holder are aligned, with the slotted wheel between them.

**Figure 5-5** Close-up of LED Holder and Slotted Wheel

**Figure 5-6** Final Modified Output with superimposed Theoretical Wave
5.4 Vernier

Using the system for identifying a single point over three hundred sixty degrees was not successful. The sine waves developed, as shown in Figure 5-6, have inconsistencies, creating duplicate data. This may be due to the quality of the slotted wheel, or perhaps the quality of the photodiode, or both.

The Vernier system is typically used in a decimal system, with ten points on the major scale and nine points on the minor scale. The result is a method to ascertain the point between two of the major scale points, as a tenth of the major point spacing.

Using the same Vernier system for one hundred eighty points, it is theoretically possible to detect one hundred eighty points between each of the major points. This would provide a resolution of .011 degrees, which is excellent for the robotic arm. However, as discussed, the resolution of the system was not able to discern this many points adequately, and was eventually abandoned.

5.5 Design to Specification

The specification for the original design criteria was for an error of less than three degrees (repeatability) [2], so the .011 degree resolution was significantly greater than this, and not required. In order to achieve the specification of three degrees of repeatability, a resolution of .1 degrees is acceptable.

In order to achieve a resolution of this magnitude, there would be only eighteen major graduations, and seventeen minor graduations. The outer diameter of the slotted wheel is 4.2 inches, dictated by the housing, with a circumference of 13.195 inches, so each of the eighteen graduations would be almost .366 inches wide. As the LEDs used are only .197 inches in
diameter, there would be a rotation of more than 5 degrees where the entire LED was either completely covered or completely exposed. This would create a dead-band that would eliminate any repeatability, and would be larger than the required resolution.

It may yet be possible to achieve some success with this method, refining the graduation width to suit the projection angle of the LED, as well as using a stamped graduation wheel instead of a printed wheel. Using the techniques described in [8], it is conceivable to accentuate the resolution further. Some raw data and graphs, as well as the calculations used, can be reviewed in Appendix 1.

It can be noted that the data shown in Figure 5-6 shows relative linearity when rotating from the bottom of the sine wave (arrow) to the top of the sine wave (arrow). This shows potential when combining with a low-resolution potentiometer. If a potentiometer can be installed that is able to show absolute position within .5 degrees, for example, then the sine wave could conceivably add resolution to at least a hundredth of a degree. This may be the ultimate encoder design for this robotic arm, having absolute position with superior accuracy.
Chapter 6: Operating System

The electrical / electronic operating system consists of a laptop computer, LabJACK U3-HV, Xbox controller, several prototyping boards (Valve Control Board, FTS Interface Board), a combination twelve volt and five volt regulated power supply, multiple relays and motor control chips, as well as several switches. There are also several wiring harnesses and many LED lights and associated resistors.
### 6.1 Design Requirements and Constraints for Re-animation

<table>
<thead>
<tr>
<th>Component</th>
<th>Design Requirement(s)</th>
<th>Constraint(s)</th>
<th>Final Component Choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software</td>
<td>Common, Expandable.</td>
<td>Cost, Supervisor familiarity.</td>
<td>LabVIEW 2010</td>
</tr>
<tr>
<td>Computer</td>
<td>Able to run Labview 2010. Able to acknowledge Xbox Controller. Must have at least one USB port.</td>
<td>Cost, Must be portable and robust for travelling</td>
<td>Panasonic CF-F9</td>
</tr>
<tr>
<td>Digital Acquisition / Interface Board</td>
<td>Minimum of 14 Output ports. USB interface to Computer</td>
<td>Cost, Interface to LabVIEW with available software.</td>
<td>LabJACK U3-HV</td>
</tr>
<tr>
<td>Human Interface Device (HID)</td>
<td>Must be able to control 7 Degrees of Freedom. Must have some variable position controls. USB Interface.</td>
<td>Cost, Robustness, Familiarity.</td>
<td>Xbox Controller</td>
</tr>
<tr>
<td>Junction Board</td>
<td>Simple prototyping board. Non-solder type board. Must have &gt;200 connections on main arm junction board.</td>
<td>Must be easily modified for different configurations.</td>
<td>Push-in Prototyping Boards, connected together for quantity of connections required.</td>
</tr>
<tr>
<td>Power Supply</td>
<td>12 volt and 5 volt regulated power. 100 Watts peak power.</td>
<td>Cost.</td>
<td>Recycled Computer Power Supply Unit</td>
</tr>
<tr>
<td>Motor Controller</td>
<td>Quad controller, (Double H-Bridge), suitable for controlling two bi-directional DC motors at 5V, 1A. Board mountable, single chip.</td>
<td>Cost.</td>
<td>SN754410 Chip or compatible</td>
</tr>
<tr>
<td>Continuity Indicators</td>
<td>Lit when power is applied to one end of the cable, to discern from backfeed.</td>
<td>Cost, Several hundred will be used.</td>
<td>5mm LED. Red and Green.</td>
</tr>
<tr>
<td>Hydraulic Pumping System</td>
<td>Provide a minimum of 3000 psi working pressure. Maximize possible flow based on available power.</td>
<td>Cost, 120 volts, 15 amps maximum available power.</td>
<td>Hydrotek 1/2 HP AC Multifunction Hydraulic Power Unit</td>
</tr>
</tbody>
</table>

Table 6-1 Design Requirements and Constraints for Re-animation
6.2 Computer

The computer chosen for this project is a Panasonic CF-F9 Toughbook, operating Windows XP operating system (see Figure 6-1).

![Figure 6-1 Panasonic CF-F9](image)

This was due to availability and software loading. It is a rugged computer able to travel without risk of causing harm to it. This is important, as the author spends much of his time travelling for work when not in the lab. The processor is an Intel Core i5 520M. There is adequate memory to run AutoCAD and LabVIEW, as speed is not a factor in this system. There are three USB ports on this computer, so an auxiliary USB hub was not required.

6.3 LabJACK U3-HV

The LabJACK U3-HV [9] is a simple to use data acquisition unit with multiple IO ports, enough to control each of the control valves on the arm (See Figure 6-2).
The LabJACK has a USB cable connecting it to the computer, and a wiring harness connecting it to the Valve Control Board (See Figure 6-3). There are eight IO screw terminals on the body of the LabJACK, and an additional twelve IO points at the bottom D-Sub connector. Most of the points can be used as either input or output, though for the final iteration, all are output points.
6.4 Valve Control Board

As can be seen, the Valve Control Board (Figure 6-3) has multiple cable pairs attached to the lower left, (output) portion of the board. These go to the FTS Interface Board, then on to the control valves. In the upper right are the valve controller chips (SN754410 chips), a typical dual motor controller used to control two valves each. The gray cable with the multiple conductors (middle right) is the lead from the LabJACK, and is used to control each of the four valve controller chips. The two conductor wire (mid right) is the five volt supply, from the regulated power supply. This is the power that is used to ultimately control the valves. In the lower left are
indicator LEDs and associated resistors, indicating when the arm is being sent a signal. Figure 6-4 illustrates the wiring of one of the motor controller chips, as typical. Only one of four motor controller and LED sets is shown, for clarity. This portion will control 2 joints.

![Figure 6-4 Schematic Circuit Diagram of Electrical Components for Two Valve Controls. This circuit is repeated 4 times in full circuit system](image)

6.5 FTS Interface Board

The FTS Interface Board (See Figure 6-5) receives the output from the Valve Control Board and transfers the signal to the individual control valves. This is primarily a junction point. The design is for simple identification of wiring, continuity testing/confirmation, and joining wires.
This system is very effective in identifying cables from the arm. Each wire from the arm is terminated on the board, with an LED for each wire, and a common resistor for each group. To identify a wire, simply apply 5 volts to the interesting wire on the arm, with the ground attached to the board. The associated LED at the interface board will light, making it easy to identify (See Figure 6-6 for partial schematic).
The valve control wires are terminated here, and when a valve is energized, the signal also lights the associated LED, as a regular continuity check. The partial schematic can be seen in Figure 6-7.
Figure 6-7 LabJACK complete with Valve Control Board with FTS Interface Board.

Note: Valve Control Board consists of 3 duplications of circuit shown in Figure 6-4

As can be seen above, the interface cables from the robotic arm are at the top of the figure, and represent ALL of the wiring to the arm, not just the control valves, but also the pressure sensors, torque sensors, and position sensors. This was completed for ease of identification of the control valve wiring, as well as knowing that eventually the other wiring will need to be identified.

All of the wires from the arm wiring harnesses are multi-strand copper, so insertion into a breadboard is difficult, and will not remain secure. Termination of each wire to the breadboards
is accomplished by attaching a male pin to each individual wire. These pins are crimped onto each wire, no soldering required. Over many manipulations, these have remained secure.

6.6 FTS Arm Wiring Harness

The wiring harness (See Figure 6-8) on the arm is typically original, with only a few minor modifications required. Some of the original plug connectors have deteriorated to a point where they are no longer serviceable, and have been removed, with the wires attached together directly, and then protected with electrical tape. The harness from the arm to the motor control cabinet is custom made, required to accommodate the four high density d-sub connectors from the arm at one end, and individual wire terminations at the FTS Interface Board at the other end.
Figure 6-8 FTS Wiring Harness (Arrows)

- Wrist Cabling
- Forearm Cabling
- Entire Arm Cabling
National Instruments LabVIEW was the software of choice, for expandability. The same control strategies for the arm could have been achieved using a microcontroller with simple coding, but the intention was to use common and flexible software as a foundation for further experimentation.

The entire program, seen in Figure 7-1, initializes the LabJACK, collects data from an Xbox controller into the computer, computes commands on the computer, and sends these commands to the Valve Control Board via the LabJACK. As there is no feedback from the arm or system, there are no inputs required from the LabJACK, although several input channels still remain for experimentation purposes. Portions of the program are reviewed in the following sections.
7.1.1 LabJACK Initialization

The LJUD OpenS sub VI (Figure 7-2) is used to identify the type of LabJACK, how it is connected to the computer, and its address (or First Found). If more than one LabJACK is used, they can be distinguished by serial number.

The LabVIEW program requires fourteen outputs, two for each control valve. During preliminary trials, six inputs were used for LED photodiodes and analog inputs, and these are still available for future experimentation. Therefore, all twenty LabJACK I/O points (0-19) are initialized in this program. This is accomplished in the U3 Pin Config sub VI. Timers and
counters are also initialized in this VI. The IO types are defined in the pink block towards the bottom of Figure 7-2. The black block to the right of the figure defines the twenty pin locations as a data array of channels.

7.1.2 Xbox Input

Query Input Devices (left Figure 7-3) is a Sub VI used to collect information from the Xbox controller. It collects data from the controller and places the data into an array.

Initialize Joystick Sub VI (right) identifies the data as that from a joystick, or controller, and forwards the array to the main control block.
7.1.3 Main Control Block

Controller info, channels, Error in, LabJACK handle, and IO types are passed into the control block (see Figure 7-4). The Joystick Acquire Sub VI continuously polls the controller, regularly updating the arrays for Axis, Button, and Direction information. This information is then accessible for the remainder of the control block.

PWM Comparator II Sub VI (see Figure 7-5) is used to split the output of the analog Axis variables into positive percentages, where the original data is a variable between negative 32,640
and positive 32,640.

This is a separate sub VI so that tuning and dead band can be modified to each of the Axis variables inside a single VI, as well, once PWM is required, it can be applied to this VI alone to affect each of the five instances. The output of this VI, a value between zero and five, is directed to an array location, which then goes to the Values Write of the Adds-Go-Get Sub VI. Note that for each PWM Comparator II Sub VI, only one of the two output variables will be active at a time. This is because the VI is used as a valve controller, powering only one side of the valve control coil at a time. The output value is between zero and five to represent the voltage applied to the coil, which is between zero and five volts.

The Adds-Go-Get Sub VI is used to collect all of the data from the initialization routines as well as getting the current information from the controller. It will step through the array, retrieving data and updating controller data continuously. It then sends output data to the LabJACK as well as reads inputs form the LabJACK through the Values Read line, making the values available to the program, if there are any. In the existing configuration, there are no inputs required or used.
Chapter 8: Testing the FTS Robotic Arm and Operating System

Once the development and assembly of the operating system was completed, testing was required in order to ensure that all of the systems were operational, and that all of the safety systems were functional and adequate. Initial testing was completed in a small lab at the Lafarge Exshaw Cement Plant, in Exshaw, Alberta, where most of the operating system development and manufacture/assembly took place.

Testing consisted of many steps. Initial tests began with simply confirming communication with the LabJACK, by turning on a simple LED using LabVIEW and inputs from the computer. Once communication was established, a prototyping board was used to mount multiple LEDs, which were controlled using LabVIEW and programmatically pushing buttons.

Motor controller chips were mounted to the prototyping board, and these were wired to LED lights, and controlled by the program. An Xbox controller was then added to the system, and this was used to control 14 LEDs, representing the 7 joints bi-directionally. Once this system was operable, a hydraulic pump, valve, and cylinder were attached to the system. The valve requires 12 Volts for actuation, so an additional power amplifier was used between the prototyping board and the valve. The cylinder was actuated in both directions using the Xbox controller, and HID testing was completed, as was control of the hydraulic system, and all of the software development. Once all systems were tested repeatedly, it was installed in the RAM lab.
The block diagram, shown in Figure 8-1, is the basis for the control system design. Note that there is no feedback in this design, and that all control is based on hand-eye coordination.

8.1 Setup in the RAM Lab

The control cabinet, complete with all of the hardware, was installed in the RAM lab as a single unit. The location for the cabinet is not ideal, as it is within the work envelope of the robotic arm. The arm should have nothing inside the work envelope, for safety, but the RAM lab has been reduced in size since the beginning of this project, and there is no longer space for the control cabinet outside of this envelope. This also means that the operator must enter the envelope in order to power up the arm. There is a remote method to start and stop the control program, but the pump, hydraulic bypass, and instrument power are controlled from the front of the cabinet.

The wiring harness from the arm was connected to the system, as were the hydraulic lines. The computer was connected to the LabJACK and the Xbox controller, so the computer and controller are outside the work envelope of the arm. Wire identification from the arm wiring harness was completed, and the system was ready to test.

8.2 Preliminary Testing

The first joint to be tested was the distal wrist joint (Joint 7), the joint that would rotate the end effector. This joint was chosen to reduce any risk of having an uncontrollable event that could cause harm to the operator or environment. It was found that this joint could be controlled exactly as predicted, moving in one direction when current was applied to the valve in one direction, and moving in the opposite direction when the current was reversed. It was also
notable, however, that once the system had hydraulic pressure, as the arm hydraulic system purged air out, the arm moved erratically until all the air was purged. Due to the design of the hydraulic system, the only way to purge air from the system is to cycle each of the actuators.

Once the first joint was tested repeatedly, another joint was chosen. This was the first wrist joint (Joint 5), chosen because it also could cause only minimal harm if it were to fail or the program lose control. This joint reacted as predicted, moving in one direction when current was applied to the valve in one direction, and moving in the opposite direction when the current was reversed, using the Xbox controller. It can be noted that there is a leak inside this control valve, causing the joint to continuously drift slightly. This valve continues to drift slightly, and there is no intention to try to make repairs at present. A replacement valve is available, at great cost and delay to the project. After this joint was actuated (with control) many times, the entire arm was wired and ready for testing.

8.3 Entire Arm Tests

Testing of the entire arm was next. The entire arm was wired to the junction board, then each of the 7 the valves were connected to the valve control board. The Xbox controller, as shown in Figure 8-2, is configured according to Table 8-1 for control. This is configurable either in the hardware or software.
Table 8-1 Xbox Configuration

The fore-arm was lifted using the 4\textsuperscript{th} joint, and the three wrist joints manipulated easily, with control. These four joints were also exercised for 10-20 strokes each, with air eventually being
purged from the system. Unfortunately, it is not possible to remove air except by stroking the actuators and allowing air to be naturally expelled.

8.4 Leak Detection and Repair

Upon leaving the system over night, a large puddle of hydraulic fluid was found under the wrist, and after a significant amount of tear-down (see Figure 8-3), a series of O-rings were identified that could be the cause, shown in Figure 8-4.

![Figure 8-3 Wrist Joint in Pieces](image)
The O-rings are in imperial sizes, and are not readily available locally. All known O-ring suppliers from Nanaimo to Sidney, including all points between, were approached, and eventually all but the rotary inner seals were found. There was material and machine time in the UVic engineering machine shop to have these duplicated successfully.

On re-assembly, it was found that the distal wrist (Joint 7) pressure sensor is still leaking. This appears to be an internal leak, as the base seals were replaced. It was decided that this small leak would be left for now, as the sensor internals were of unknown design, and there was little possibility of having the correct seals to replace any failed ones.

8.5 Continued Testing

Moving forward with testing, the shoulder joints were tested next. First, the upper arm was raised using the third shoulder joint (Joint 3). When the elbow (Joint 4) was in the extended position, the arm would not lift at all, and it would only move upward when the arm was ‘flexed’
position, bringing the center of mass closer to the shoulder. Once the joint was cycled several times, the response was better, but still not perfect. With the installation of a higher-displacement pump, improvement is expected in performance. There is no pressure indicator in the system, and the actual outlet pressure of the hydraulic pump has never been confirmed, and this may be part of the problem as well.

The second shoulder joint (Joint 2) was then tested with similar results, getting better as the air was purged. The first shoulder joint (Joint 1) was last to be tested, again with the same results, better each cycle. However, even after multiple cycles, it was still found that the arm could not be elevated using any of the three shoulder joints while Joint 4 was extended.

Each joint was rotated from extent to extent, and the rotation angles and rotation times are shown in Table 8-2 below. Note that these are the best times, with the arm positioned in a neutral position, so there was no work done.

<table>
<thead>
<tr>
<th>Joint Number</th>
<th>Degrees of Rotation</th>
<th>Rotation Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>20 seconds</td>
</tr>
<tr>
<td>2</td>
<td>317</td>
<td>15 seconds</td>
</tr>
<tr>
<td>3</td>
<td>210</td>
<td>12 seconds</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
<td>8 seconds</td>
</tr>
<tr>
<td>5</td>
<td>180</td>
<td>6 seconds</td>
</tr>
<tr>
<td>6</td>
<td>180</td>
<td>5 seconds</td>
</tr>
<tr>
<td>7</td>
<td>360</td>
<td>5 seconds</td>
</tr>
</tbody>
</table>

Table 8-2 Joint Rotation Angle and Duration
8.6 Work Envelope

The work envelope of the arm is based on the length of each arm segment and the angle of rotation of that segment. Once all of the joints were in full control, it was found that the arm could come in contact with itself readily, as well as touch the support stand, which is generally very difficult and rare in modern design. Modern design typically protects the mechanisms from causing interaction between their components. This is a dexterous arm, designed to fold into a compact envelope for space travel (see Figure 8-5), so the ability to ‘touch itself’ is not avoidable. It is, however, a requirement, once the position sensors are installed, to place limits in the control system to eliminate the ability for the arm to cause harm to itself.

Figure 8-5 Telerobot in Stowed Configuration
There is also the environment interaction that can be a problem. The arm can interact (make contact with) with the ceiling, the walls, the floor, and the control cabinet. In order to prevent harm to the environment, there should be limits placed in the software once the position sensors are available. With the current hydraulic pump, the motion is very slow and contact with itself and the environment can generally be avoided, though it is possible.

The arm will stay in a stationary position, (aside from the wrist joint drifting) until the hydraulic pump is turned off. Once the fluid pressure is eliminated, the arm slowly collapses to the floor. It is believed that this is a symptom of internal leakage of the valves, where there is an overbalance applied by the arm to the valves through the cylinders, causing the valves to displace and allow fluid to shift from the high pressure side of the actuator to the low pressure side. This does not happen while the pump is operational because the pump pressure is greater than reactionary pressure from the arm. The uncontrolled motion is not due to leakage across the hydraulic piston, as the design has an atmospheric gap in the actuator, (between the cylinders, at the rack and pinion gear set) where a leak would be evident. In order to avoid unexpected movement after shutting the system down, the arm must be placed in a position of lowest possible energy, such that the arm will rest on the floor, a stand, or other, so that it cannot fall further.

The final product of this project is an operational robotic arm, designed by NASA-Martin Marietta, manufactured by Western Space and Marine, and animated by John Keen, P.Eng. All of the components for the operating system are stored inside the control cabinet, aside from the computer. Any computer, loaded with the operating system software, will be able to be plugged into the operating system and have the arm operational. The only requirements for the computer
are that it has multiple USB I/O ports, be capable of running LabVIEW, and be able to recognize an Xbox controller.

Figure 8-6 Final Product: Operational FTS Robotic Arm
Chapter 9: Discussion

9.1 Description

The project to animate the FTS Robotic Arm started in 2010, and culminated with the successful animation of the arm in 2015. The project began with installation and assembly of the arm, then with investigation of the position sensors. While looking into these, the donor indicated that there were secondary position sensors. The secondary sensors were actually found to be torque sensors, after some reverse engineering of the circuit, and then powering them up. The pressure sensors were not available to be experimented with until late in the project, and have not been addressed.

The time taken to address position sensing was significant. Many hours were dedicated to research of the existing sensors, and many more were dedicated to research of an alternate sensor, the Vernier Optical Encoder (see Appendix 1). Finally, after many hours of experimentation, with limited positive results, the project was refocused to the animation of the arm.

9.2 Hydraulic System

The hydraulic system on the arm is the only thing required for animation. The basic requirements for functionality are: Pump, Power Supply, Switches, Hoses, and Wiring. The pump could be any readily available and relatively inexpensive pump. The voltage required to actuate the valves was calculated using the resistance of the valve coils and expected amp rating, published in the valve manual. In order to ensure that excess amperage was not possible, and not having a current limiter, five volts was chosen as the maximum voltage available to apply to the valve. This was found in a recycled computer power supply. The switches to control the valves
could be any double pole triple throw switch, wired as an H-Bridge. Hydraulic hoses connecting the pump to the arm are required. The wires for the valves were easily identifiable, and a complex interface system was not required to get power to the valves. A working system could be operational with a very minimum of effort and investment.

Animating the arm, as interpreted by the author, was not just to make it move, but to use the tools and systems and skills developed during the years spent as a masters student to control the motion of the arm, and be able to offer a system to the RAM lab that is worthy of building on and experimenting further with. By installing a permanent cabinet to keep the system components safe, and an interface board to collect all of the wiring from the arm into a single, simple location, and implementing a valve controller board and LabJACK, the system is simple to connect to a computer. This could have satisfied all of the requirements for animation, using the keyboard on the computer to actuate the valves. However, as the author has some experience operating heavy equipment, and knowing that many people likely to work with this arm are familiar with the typical Xbox controller, it was a natural fit to implement the Xbox controller to control the arm.

The arm is now fully controlled, using the Xbox controller as the HID, and having visual feedback. The torque feedback is available for implementation, though a second LabJACK will be required, as the existing one does not have enough remaining I/O. The pressure feedback is also expected to be available, and could be wired to the same LabJACK as the torque feedback unit. The position sensor is the most important piece of equipment missing from this robot, and a solution is not readily available, though an optical quadrature-based encoder would be relatively simple to create and install.
Once the position sensors have been installed, and the work envelope and limits have been defined in order to ensure the robot is not able to damage itself or the environment around it, a more powerful pump will be required in order to be able to move the arm faster, even when fully extended.

9.3 Contributions

- Design of the absolute encoder given all the strict design requirements of Table 5-1.
- Design of a new control strategy for the robot arm using cost-effective modern controllers (Xbox HID), and data acquisition systems (LabJACK), and modern LabVIEW software.
- Development of the control code.
- Reverse-Engineering a robotic system with little/no documentation of any kind.
- Re-Animating the entire system by installing the physical connection between electronics and hydraulics.
- Donate the hardware to the RAM Lab for future endeavors.
Chapter 10: Conclusions and Recommendations

The exercises completed during this project have identified several items that can be addressed by the next student. The most significant is the position sensing. This is critical to know where the end effector is, and is required to complete any kinematics or reverse kinematics.

The leaks in the hydraulic system should be addressed prior to trying to make any controlled manipulation, even though a tuned feedback system can overcome the bypass issues seen in the wrist.

The next most important system to be addressed is the hydraulic pump. The existing system has proven adequate for proving concepts, but is not appropriate for completing any work. Once the leaks are repaired, a constant-pressure pump (variable displacement) with a small accumulator will prevent the arm from collapsing when the pump is shut down, as well as allow the arm to move in all directions regardless of extension or joint position.

Once a pump of appropriate displacement is installed, it will be crucial to rewrite the PWM Comparator II block, so that it has a proper PWM output, in order to take advantage of the proportional control valves. If the existing on-off control is used, the speed of the arm will not be controllable, and may move too fast to be safe.

The end effector (EE) is a complex tool, and has yet to be acknowledged. It is beyond the scope of this project, and has not been addressed. In order to make the robotic arm a useful training tool, it should be able to grasp, not just touch. The EE purportedly has multiple motors and force feedback loops. It would be very useful to have an operable EE for training purposes. The end effector on this arm has an exchangeable tool holder, making it relatively simple to
exchange tool tips from gripper (attached) to screw driver or probe tips, which are not available at present.

Pressure and torque sensors will be useful once the system is completely functional, including all of the kinematics and reverse kinematics being programmed. This is because the torque (or pressure) applied to a particular joint has no meaning if there is no information available about position or movement of the joint. The torque about each joint is eventually to be used as a cumulative moment to calculate the force vector that the EE is applying to the environment.
REFERENCES


[5] Chris Roper, “Flight_Telerobotic_Servicer”, Roper Resources Ltd. 984 Patrick Street, Victoria, BC, Canada V8S 4X5


Appendix A: Vernier Optical Encoder

The Vernier Optical Encoder (VOE) is a theoretical encoder where there are two sine waves developed using an LED and photo diode pair for each sine wave, each developed at a known frequency (180 vs 179 cycles per revolution). Knowing that it is possible to ascertain position within a single cycle of the sine wave very accurately (depending on quality of slot and filters on LED and receiver), it is possible to identify the singularity where two perfect sine waves of known frequency would have a single point where the found values would exist.

For example, using a single slotted wheel with 180 slots, and driving the output voltage from the photodiode from 10 volts to .6 volts, which would occur from one degree to the next, such as when the system is at 0 degrees, the LED would be perfectly aligned with the slot, and the output of the photo diode would be 10 volts, and when the system is rotated to one degree, the slot would be solid between the LED and photo diode, with an output of .6 volts. Using equations such as:

\[ \cos X = Y \]

Equation 1

or

\[ A\cos Y = X \text{ or } (360 - X) \]

Equation 2

and

\[ Y = A \cdot \sin B \cdot X - D + C \]

Equation 3
Where:

\[ A = \text{Amplitude from center} = \text{maximum voltage} - C \]

\[ B = 2\pi/\text{Period}, \ \text{Period} = 2\pi/180 \text{ or } (360/180)\pi/180 \]

\[ C = \text{Voltage of Centerline} = \text{average voltage} = (\text{High voltage} - \text{Low voltage}) / 2 \]

\[ D = \text{Phase Shift (independent)} \]

\[ X = \text{Position} \]

\[ Y = \text{Voltage} \]

Solving Equation 3 for \( X \), one gets:

\[
X = \frac{ASin \frac{Y-C}{A}}{B} + D \text{ or } 360 - \frac{ASin \frac{Y-C}{A}}{B} + D
\]

Equation 4

Using Equation 4, knowing \( A \), \( B \), \( C \), \( D \), and \( Y \), position \( X \) can be solved. Note that over 2 degrees, there are 2 potential solutions, and with this information alone, the derivative of the position must be known (positive or negative slope), as well as the direction of motion. In order to unitize the information to a single degree, the position \( X \) will be divided by 180, the number of slots in the ring, shown in the following Equation 5:

\[
Pp = \frac{Xp}{180} \text{ or } \frac{360 - Xp}{180} + 2N \text{ cycles}
\]

Equation 5

Where \( Pp \) is the Actual position and \( N \) is the number of cycles from zero,
and $V_p$ is the Vernier position and $M$ is the number of cycles from zero for the Vernier scale (see Equation 6). It can be noted that $P_p = V_p$, so Equation 5 = Equation 6, or

$$\frac{X_p}{180} + 2N \text{ cycles} = \frac{X_v}{179} + \frac{360}{179} M \text{ cycles}$$

Equation 7

or

$$\frac{X_p}{180} + 2N \text{ cycles} = \frac{360 - X_v}{179} + \frac{360}{179} M \text{ cycles}$$

Equation 8

or

$$\frac{360 - X_p}{180} + 2N \text{ cycles} = \frac{X_v}{179} + \frac{360}{179} M \text{ cycles}$$

Equation 9

or

$$\frac{360 - X_p}{180} + 2N \text{ cycles} = \frac{360 - X_v}{179} + \frac{360}{179} M \text{ cycles}$$

Equation 10

Now resolving each of the 4 equations for $N$, knowing that $M$ is equal to either $N$ or $N-1$, and also knowing that $N$ is an integer, eight equations result. Each of these eight equations will be solved for $N$ and calculated. Only one equation should result in an integer for $N$, and $2N$ is the
number of whole degrees to the actual position. The decimal portion of the position is found using the appropriate version of Equation 5.

Figure 0-1 VOE Raw Data Screenshot Excel Graph

The raw data, graphed in Excel, as shown in Figure 0-1, looks promising and clean, easy to see that there are reasonable sine waves available for manipulation. However, upon collecting a denser cloud of data, and removing any data smoothing, as seen in Figure 0-2, it can be seen that there are wide and narrow portions to the sine waves, as well as duplications in the values and long pseudo-linear sections. These discrepancies make using this style of system impossible to use.
Figure 0-2 VOE Raw Data LabVIEW Screenshot
Figure 0-3 Raw Data with Superimposed Sine wave

Raw data with a superimposed sine wave are shown in Figure 0-3, and the discrepancies are obvious. Manipulating the data with capacitors and resistors did not improve the curve significantly, and may only falsely improve the data.
Figure 0-4 Raw Data over 180 Degrees

Figure 0-4 shows the raw data over 180 degrees, and the difference in frequency is apparent. On zooming into a particular section of data, however, it is found that the data is still not clean, and a singularity is not possible to identify. However, to peek interest, and confirm that it may yet be possible, notice the ‘ghosting’ in Figure 0-4, showing a superimposed sine wave and negative sine wave, each with a single cycle over the one hundred eighty degrees.
Figure 0-5 Close-up of Portion of Figure 0-4