Remote Control of Hydraulic Equipment for Unexploded Ordnance Remediation

by

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Abstract

Automation of hydraulic earth moving and construction equipment is of prime economic and social importance in today's marketplace. A human operator can be replaced or augmented with a robotic system when the job is too dull, dirty or dangerous. There are a myriad of applications in both Government and Industry that could benefit from augmenting or replacing an operator of hydraulic equipment with an intelligent robotic system

A specific important situation is the removal of unexploded ordnance (UXO). The removal of UXO is a troubling environmental problem that plagues people around the world. This document addresses the danger that UXO pose to military groups in applications such as active range clearance and disposal of unexploded or dud munitions. Disposing of these munitions is a difficult problem, which first begins by determining their location. The process can be aided through the use of teleoperated hydraulic equipment, which allows the operator to be located at a safe distance from these munitions. In the past, converting a large piece of hydraulic construction equipment for teleoperated use has been an expensive task. An important result of this research is demonstrating that through readily available commercial products and existing design methodologies, such robotic tasks can be accomplished at relatively low cost and in a timely, reliable fashion.

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Acknowledgements

Working on this project has been one of the most exciting experiences of my collegiate career, and it has added pages to my engineering skills and competencies. Completion of this project would not have been possible were it not for the gracious contributions and overall engineering acumen of the faculty of the Mechanical Engineering Department of Virginia Tech.

I have always been interested in robotic systems, and I owe my beginnings in this field to the invaluable tutelage of Dr. Reinholtz, whom I have worked with on the Autonomous Vehicle Team for the past three years. Dr. Reinholtz has presented me with countless research opportunities in the field of unmanned vehicle systems and robotic systems alike. I am extremely grateful for his endless support as an advisor. This project would also have not been possible were it not for the ongoing relationship that Dr. Wicks has had with the Navy. Dr.Wicks's watchful eye over the project was a loadstone from which all members found direction. Development of a teleoperated system requires a concerted understanding of a broad range of engineering skills, and this breadth was found and strengthened through guidance I found in relations with Dr. Saunders and his Mechatronics class. Any robotics application invariably requires an understanding of control theory, because it would not be a robot if it didn't have dynamics! This being said, I owe my strong love for Control Theory to the motivating educational credo of Dr. Leo's series of controls classes.

Building the teleoperated excavator was an arduous task, but through the help of many project members, astonishing results have been attained. I would like to thank George Clotfelter for having confidence in our design choices and also for supplying us with the materials and monetary compensation that made this project possible. George was an excellent project mentor, and he gave a magnitude of his time as a sounding board for all of our ideas, no matter how strange they may have sounded. This relationship with the Naval Surface Warfare Center is extremely valuable, and I look forward to hearing about future relations with Virginia Tech.

My, acknowledgements would not be complete without mentioning those who gave their blood, sweat, and tears to make this project complete. I want to thank Michael Fleming and Ian Hovey for all the hours that I required them to spend on this project. Ian was our hydraulics designer, and his unique mechanical insight was a key factor that got this project moving and has kept the machine running even today. I especially want to thank Michael for the hours of eye-straining programming that he endured. His ability to grasp a programming concept and put it into motion is a sight to see. While we tried hard to blame anything that went wrong on software, Michael often proved us wrong. I would also like to thank Michael Cummins for his extreme devotion to the project. He has been an active member of the project whenever or wherever possible. As the safety officer, he is the only member that has bled for the project and his country as well! I would like to thank National Instrument for their continued support and extensive publicity of the project, specifically Brian MacCleery and Eric Dean. Other key contributors to the project were Mike Sukits, Byron Collins, and Marty Benz.

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Chapter 1 – Introduction

Industrial automation is of prime economic importance in the today's marketplace. Automation of hydraulic construction equipment is a growing area of research [1]. Distinct opportunities for the intervention of robotic systems exist where work is either exceedingly repetitive or too dangerous. [2]. Often, the need for higher efficiency drives this research, but also the need for an added level of security is manifested.

In addition to the dirty and tedious nature of the work, heavy equipment operators must sometimes endure the increased risk of handling hazardous materials such as chemicals and explosives. Insurance costs and slow rates at which these extremely sensitive jobs can be completed yield prohibitive costs. A solution to this dilemma is found in the ongoing research of unmanned robotic systems, which have no problem performing a multitude of dirty, dull, or dangerous tasks.

1.1 Project Overview

Originating in February of 2002, the project outlined in this document began as research challenge from the Navy to Virginia Tech. At the onset, the goal was to equip a stock excavator with remote control capabilities for removal of unexploded ordnance. The team at Virginia Tech accepted the project with no pre-determined solution.

Members of the Naval Surface Warfare Center in Dahlgren, VA (NSWC) came to the Mechanical Engineering department at Virginia Tech, and explained that they needed a device that could safely remove buried unexploded ordinance. The potentially large quantity and size of these munitions along with the depth at which they could be buried warranted the use of a large tracked excavator. The inherent danger of the mission required the operator excavate these munitions from a safe distance of at least 3000 feet. The solution proposed by the research team was to retrofit a 16-ton CASE CX160 tracked excavator for wireless use at a distance of at least 3000 feet (Figure 1-1).

The focus of this document is to explain the design of a specific more intelligent machine that was developed for the Navy to aid in a sensitive environmental clean-up project. Through a historical review of related topics, evidence will be presented demonstrating that technology developed in building a teleoperated excavator has great relevance in today's economic climate. But, the major focus of this document is to serve as a tool that will foster the development of unmanned systems in the field of hydraulic equipment automation. The teleoperated system presented herein is unique, because of its low cost and the extensive use of commercially available components and software.

Figure 1-1: Remotely controlled CASE CX160 excavator

1.2 Motivation

The goal of this project was to create a reliable, working excavator for the Navy to use in unexploded ordnance remediation. Although the goal was to deliver a working device in six months, the project seemed to be much more than the six-month mission.

Research on this project both parallels and stems from current efforts in the United States Government and other national and international institutions. Future Combat Systems (FCS) is an initiative aimed at bringing the United States Military into the 21st century [3]. One part of the FCS initiative is the Joint Robotics Program (JRP), which "serves as a catalyst for insertion of robotic systems and technologies into the force structure" [3]. The vision of the JRP is that military robotic systems will "proliferate throughout the 21st century force structure, performing dirty, dangerous and dull tasks" [3]. This vision is consistent with Virginia Tech's design of the teleoperated excavator.

1.3 Technical Challenges

Teleoperated control of large mechanical systems is challenging. Remote control of a hydraulic system such as the CASE excavator entails important design decisions in the areas of software design, hydraulic conversion, wireless data transmission, safety and electronics.

Notable challenges in the area of hydraulic design involved valve selection and placement of those valves within the original equipment. The interaction of electrohydraulic components with the original mechanically actuated system produced dynamics effects that required extensive diagnostics and subsequent analysis. Flow rates, pressure ratings, and system response receive attention in the design of the hydroelectric conversion.

The astute software engineer must pay close attention to robustness, while maintaining modularity. Since control information for the excavator is transmitted wirelessly, software is designed to minimize the required bandwidth while maintaining the necessary control update rates. In a reliable, time-critical control system, wireless data connectivity must be assured [4]. Challenges arise in selecting components that afford reliable data and video transmission lines at acceptable rates and ranges. Also, the design engineer must always be aware of radio interference.

In addition to the design challenges mentioned, the remote controlled excavator project described in this document had to be built in a limited time frame and under a strict budget. In only six months, a team of two graduate students and five undergraduate students conceptualized, designed, built, and delivered a working teleoperated excavator.

Any design process demands thoughtful decisions; however, the breadth of topics involved in the design of the teleoperated excavator required decisions that spanned a number of engineering disciplines. This document will present an overview of the design. The interested reader should consult the cited references for further information on the commercial products and subsystems that were implemented.

Chapter 2 – Literature Review

The spectrum of unmanned systems is broad and the various projects described in literature are often task specific [3]. In order to understand the scope of the teleoperated excavator project, it is important to understand the current spectrum of unmanned systems and where remotely controlled hydraulic systems fit within this spectrum.

2.1 Unmanned Robotics Spectrum

Robotic systems are defined and classified in a number of ways. Robotic systems can be classified by factors such as weight class or tasks that the systems are designed to perform, but the predominant classification method is by intelligence level [3]. What decisions does the robot make on its own? How many decisions can it make before needing more input from a human operator, or is a human operator necessary at all?

The simplest robot is a tethered, teleoperated robot, where actuation commands are sent directly to the robot via wire. The most complex robots require only to be turned on. They can then make decisions and performs tasks consistent with its mission until it either runs out of power or refuels itself. These cases represent opposite ends of the spectrum of robotic systems. The goal of robotic design is to develop and proliferate systems that progress towards full autonomy [3].

The teleoperated excavator is on the opposite side of the spectrum from the autonomous unmanned system. While the excavator incorporates some automated tasks, a human operator controls the main mission goals and inputs. This limited level of autonomy allows the operator to change mission objective quickly. Robotic systems with a high degree of autonomy can be task specific and difficult to modify for new mission goals. The teleoperated excavator can be used in as many ways as the original piece of equipment.

Teleoperated systems are being asked to accommodate an increasing breadth of tasks. Areas of application extend from microsurgery to deep-sea exploration. The term, Teleoperation, simply means, “doing work at a distance.” However, the “distance” term is vague. It can refer to physical distance but can also refer to scale. A surgeon using micromanipulator technology to conduct surgery on a microscopic level is an example of scaled teleoperated system. The teleoperated excavator was required to work with the operator located at a distance of 3000 feet.

Unmanned systems will thrive with improved technology, which will pave the way for increases in intelligence and capability of these systems. There is a need for greater numbers of unmanned robotic systems. Increased computational speeds and falling costs will herald their development. Unmanned robotic systems will make their home in the dirty, dull, difficult, and dangerous environments [3].

2.2 UXO Removal Programs

Removal of unexploded ordnance (UXO) has historically lent itself well to teleoperated robotic systems. Munitions are often in unknown states and locations, and the risk of interacting with these munitions requires the operator to be located at a safe distance.

There are distinct challenges in removing UXO, which begins by locating them. Upon locating the ordnance, one must choose the correct system to remove it. Ordnance size and depth will govern type of device needed to extricate it [5]. UXO removal efforts consist of four categories defining the type of hazard, but the location of these munitions can vary greatly, as shown in Figure 2-1. Ordnance located in a combat zone, such as the Counter Mine (CM) zone requires an altogether different removal approach than that of Active Range Clearance (ARC) or UXO Environmental Programs (UER). The other two areas, mentioned in Figure 2-1 are the noble efforts of Humanitarian Demining (HD) and Explosive Ordnance Disposal (EOD) as it pertains to unused or dud munitions. The teleoperated excavator can find use in many of these areas. However, the purpose of this project is to build a device that works mainly in the EOD and ARC areas removing on-base munitions.

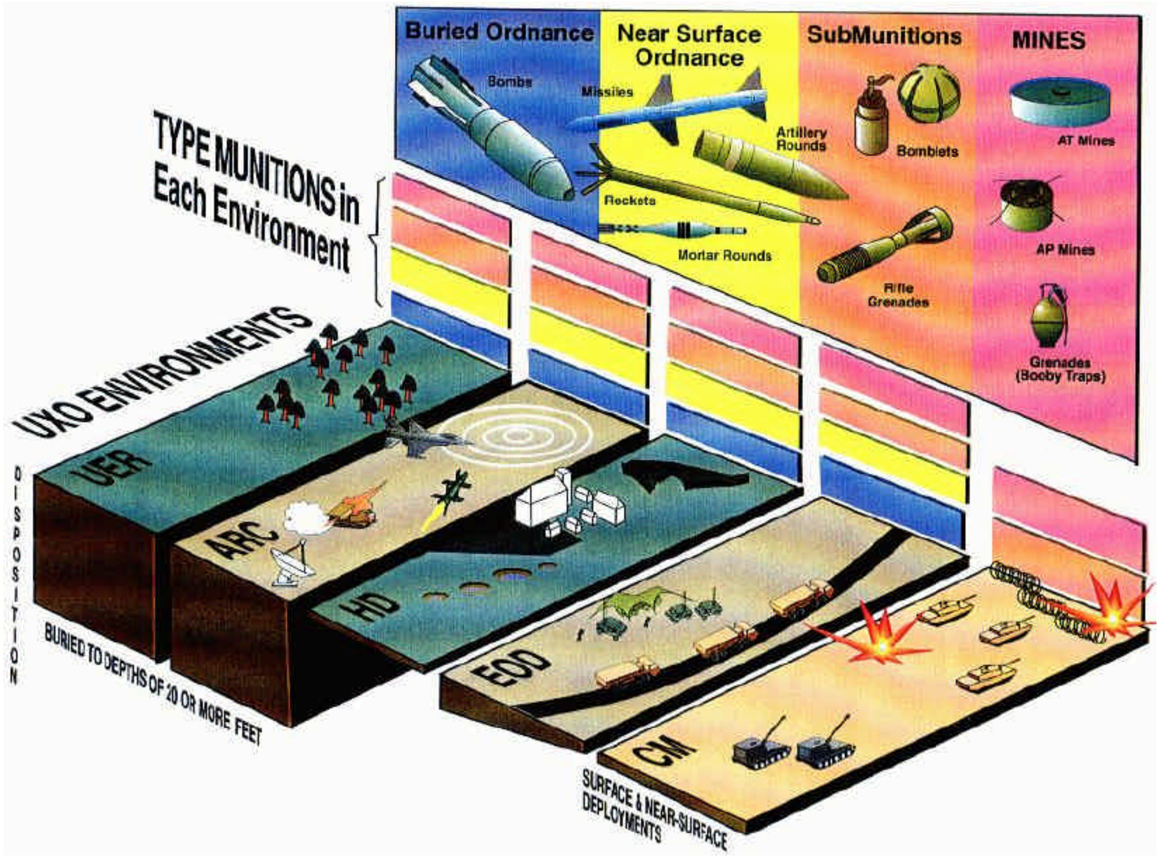

Figure 2-1: UXO environments and munitions [5]

With the formation of the Joint Robotics Program by Congress in 1989, which directed consolidation of robotics programs, robotic research in the area of UXO has flourished. Air Force Research Labs (AFRL) has risen as one of the key players in UXO efforts [3]. AFRL began developing large equipment for active range clearance as well as EOD applications. Heavy construction equipment such as a CAT Excavator and a DZG dozer were outfitted with teleoperated capability. The research has been consolidated into the All Purpose Remote Transport System (ARTS) [3], [6]. These projects are shown in Figures 2-2 and 2-3.

Figure 2-2: Advanced Automated Ordnance Excavator (AAOE) [6]

Figure 2-3: AFRL DZG teleoperated dozer (ARTS) [6]

The ARTS program is effort to build multi-task platforms, although mostly focusing on ordnance removal. ARTS can be seen fighting a runway fire in Figure 2-4. AFRL is not the only player in unexploded Ordnance removal. The Unmanned Ground Vehicle/Systems Joint Project Office (UGV/S JPO) performed work with a Panther tank, which can be seen performing mine removal Figure 2-5 [3].

Figure 2-4: ARTS fighting a runway fire [3]

Figure 2-5: Teleoperated turretless M-60 Panther detonating anti-personnel mine in Bosnia [6]

Development of robust teleoperated platforms paves the way for more intelligent systems that do not need constant operator input. The Advanced Automated Excavator seen in Figure 2-2 has advanced from teleoperated control to a vehicle with the autonomous capability of, "locating itself in a position to retrieve buried ordnance" [6]. Although discussion to this point has been focused on US Military efforts, efforts have been made to develop remote controlled excavators in Australia at University of Technology and Monash University [7], [8]. Also, the United Kingdom's Ministry of Defense has a small robotic program focused on teleoperated combat applications, which include UXO, as seen in Figure 2-6 [6].

Figure 2-6: UK's single Hagglunds automotive platform teleoperated vehicle [6]

While, a multitude of research has been performed in the area of UXO removal as it pertains to heavy hydraulic equipment, much of this work is performed under large budgets and long time frames [3], [5], [6]. The funding for the ground robotics element of the Joint Robotics Program totaled 27.6 million dollars in 2002. UXO efforts consisted of close to $20M of the total budget, and many of these programs have been in operation since 1998. While, this budget consists of a myriad of efforts, programs such as ARTS have received over a million dollars a year. The evidence of this document will demonstrate that high cost and long design time frames are not necessary to build a teleoperated device capable of removing unexploded ordnance.

Chapter 3 – Design Objectives and Constraints

The specific goal of the teleoperated excavator, constructed for the Naval Surface Warfare Center (NSWC), will allow an operator to perform exploratory digging to locate unexploded ordnance and chemical munitions at a safe distance. In order to understand the customer needs and formulate design objectives a background of NSWC Dahlgren is offered. The applications of remotely controlled construction equipment exceed beyond specific tasks for which the Navy requires its service.

3.1 NSWC Background

One of the missions of NSWC Dahlgren is to test the Navy's arsenal of surface warfare munitions. Located on the Potomac River south of Washington, D.C., NSWC supplies weapons testing personnel with a firing range spanning over 30 miles down river, as seen in Figure 3-1 [9]. To date, NSWC Dahlgren is the longest inland open-water firing range in the world [9], [10]. The proximity to Washington and the Naval shipyards in Norfolk, VA has enabled the base to test weapons systems for many years. There are a number of tests that NSWC Dahlgren has performed over the years. A prime initiative includes operational testing to determine accuracy; however, the days of 16-inch battleship fired shells have passed and given way to rockets. Thus, the firing range is currently used primarily for only 5-inch shells.

The same rigorous testing of these munitions must still be performed. Munitions are tested to endure extreme shocks such as a 40-foot drop test, and they are expected to withstand vibrations seen in transport. Munitions must survive high heat over short and extended periods without detonation. A successful test results in unexploded ordnance.

Following current testing, munitions are disposed of using additional explosives, but this has not always been the practice. Half a century ago, Dahlgren was far from any major city, and unused ordnance was often buried on base. Munitions ranging from small blasting caps to large 2000-lb bombs were discarded and buried in ammunition dumps. Recent efforts to expand the base require remediation of these live ordnance sites [10].

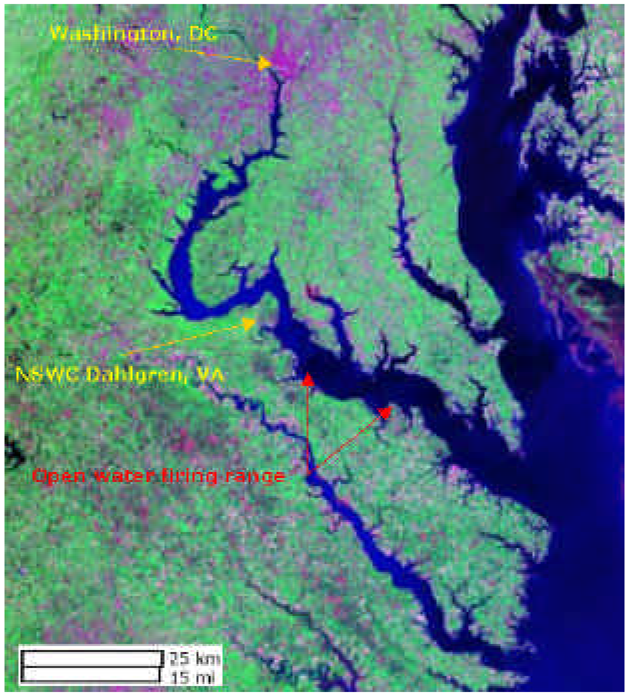

Figure 3-1: Naval Surface Warfare Center firing range

3.2 Design Considerations

The first step in any design process is to identify customer needs. Design goals must be tailored to meet all customer needs and exceed customer expectations. Marketing a similar product to other industries requires a similar in-depth look at customer needs.

Customer Requirements. Mandated by NSWC Dahlgren, the teleoperated CASE CX160 excavator must have operation capability at a line-of-sight range of at least 1500 feet. Control of the excavator should be as similar as possible to conventional operation. Due to the possibly large size of munitions, the excavator requires no protective elements. The excavator has been deemed expendable, however steps should be taken to assure that accidental detonation does not occur. The excavator will be equipped with a thumb to aid in extrication of large ordnance as see in Figure 3-2.

High dexterity and control should be augmented with an extensive visual and auditory feedback systems. Additional feedback systems, such as force feedback, should be considered but are not required. The equipment used for teleoperation should be reliable and resistant to all weather elements, and the equipment should be easy to service.

Figure 3-2: Excavator bucket with attached thumb

In addition to the vision and control system, the teleoperated excavator should boast a fail-safe emergency stop system operating separate from the other systems. Lastly, NSWC stipulated that conversion to conventional operation of the excavator should take no longer than thirty minutes.

These customer requirements were assimilated and the overall solution is presented in Chapters 4 and 5. The urgent need of the environmental clean-up project required a working design be constructed in less than six months. It was determined that the best avenue for developing the system warranted purchasing as many off-the-shelf components as possible to speed up development time.

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Chapter 4 – Overall Solution

This section serves to present an overview of the solution to designing a remotely controlled CASE CX-160 tracked excavator (Figure 4-1). The design meets and exceeds all customer requirements mentioned in Chapter 3. Detailed information of subsystems of the teleoperated excavator can be found in Chapter 5. The teleoperated excavator was completed in six months for under $20k total parts cost. Fast lead-time and cost effectiveness was made possible through the use of modular products. The design enables the excavator to be rapidly deployed and serviced. Through modularity and cost effectiveness, this design of a teleoperated excavator can be replicated on a variety of other hydraulic platforms for service throughout the Military and Industry.

Figure 4-1: CASE CX160 tracked excavator [11]

Hydraulics. Outfitting hydraulic construction equipment for remote operation begins by selecting an actuator. Operating pressures up to 8000-psi are common in hydraulic construction equipment. Selecting the correct valve to port this pressure and flow is essential, and the accuracy of the components determines the level of complexity of the surrounding control system.

The Case CX160 excavator is operated by conventional means with two dual-axis joysticks and two single-axis foot pedals (Figure 4-1). The arm, boom, bucket, swing, and left and right track make up the six degrees-of-freedom (Figure 4-2,3). These axes are actuated through two hydraulic stages, a low-pressure pilot system that includes spool valves and high-pressure system including the main cylinders. The spool-valves serve as a link between the pilot system (500-psi) and the main system (5500-psi). *Hydraforce* electronically controlled valves interface with the hydraulics in the pilot system and provide remote control of the excavator [12]. Interfacing at 500-psi is safer, and lower flow rates yield more choices of electronically controlled valves.

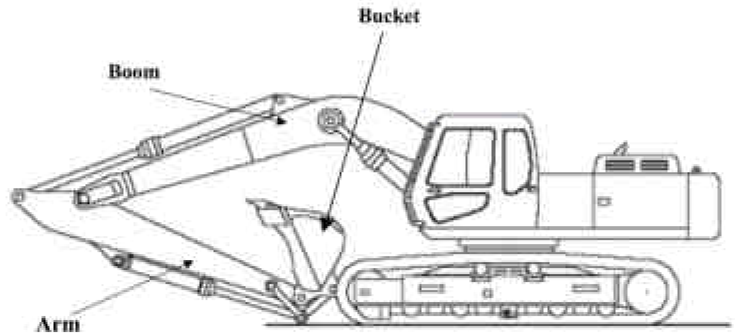

Figure 4-2: Six degree-of-freedom of a tracked excavator (side view)

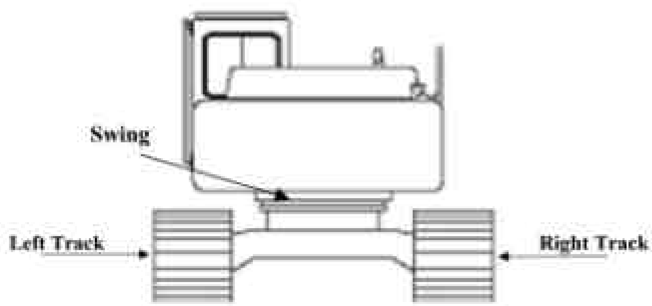

Figure 4-3: Six degree-of-freedom of a tracked excavator (rear view)

The electro-proportional valves on the excavator are solenoid operated, pressure reducing/relieving control valves. Proportional valves are more cost effective than servo valves, but price is traded for accuracy and response time [13]. For the design purposes of this project, the unneeded accuracy is traded for the cost benefit yielding a cost savings of over $12k.

In order to revert to conventional drive in thirty minutes, the proportional valves are plumbed into the system using shuttle valves. More detail on the hydraulic design is offered in Chapter 5. The system can be operated at anytime by either conventional or remote controls.

Electronics. The ultimate goal in electronic equipment selection is reliability. All components must be able to withstand a large range of temperatures, vibration and endured use. The solution could be found in a product produced by *National Instruments* (NI) called FieldPoint [14].

FieldPoint is a compact and rugged distributed I/O system. The real-time operating system that FieldPoint boasts is a crucial attribute for any time-critical application such as the control of a

16-ton excavator. FieldPoint is configured to run a proprietary software system developed by NI called LabVIEW [15]. The modular capability of FieldPoint provides a customizable number of digital and analog I/O. Serial and ethernet ports also increase connectivity.

FieldPoint is the backbone of the teleoperated excavator. Two sets of network modules, seen in Figure 4-4, are employed, two on the excavator and one at the remote station. Feedback and control information is assimilated by each of the FieldPoint modules through joysticks, switches, and connections to additional computing components. The network modules communicate with each other through serial and ethernet protocols. Wireless serial radio modems provide the connectivity between the network modules.

Figure 4-4: FP2000 network module [14]

The serial radio modem is a *Data-Linc* SRM-6000 radio modem [16]. Selected for its excellent data throughput of up to 115.2 kbps, the SRM-6000 boasts a range of up to 25 miles line-of-sight. Additional detail on this device is offered in Chapter 5. The reliability and speed of these supporting computing systems offer transparency, which enables the necessary control update rates.

Wireless 2.4 GHz, discrete-frequency transmitters send audio and video feeds to the operator station. The operator can pan, tilt and zoom one of the three cameras, and auditory feedback allows the operator to hear the engine (Figure 4-5).

Figure 4-5: Teleoperated front viewing vision system

Additional features such as fuel level, oil temperature and water temperature can be read on the user interface. The user interface, seen in Figure 4-6, is monitored using a web browser on a networked PC. The operator can interact with the excavator through joysticks, foot pedals, and other switches that start the machine, turn on video feeds, and enable control.

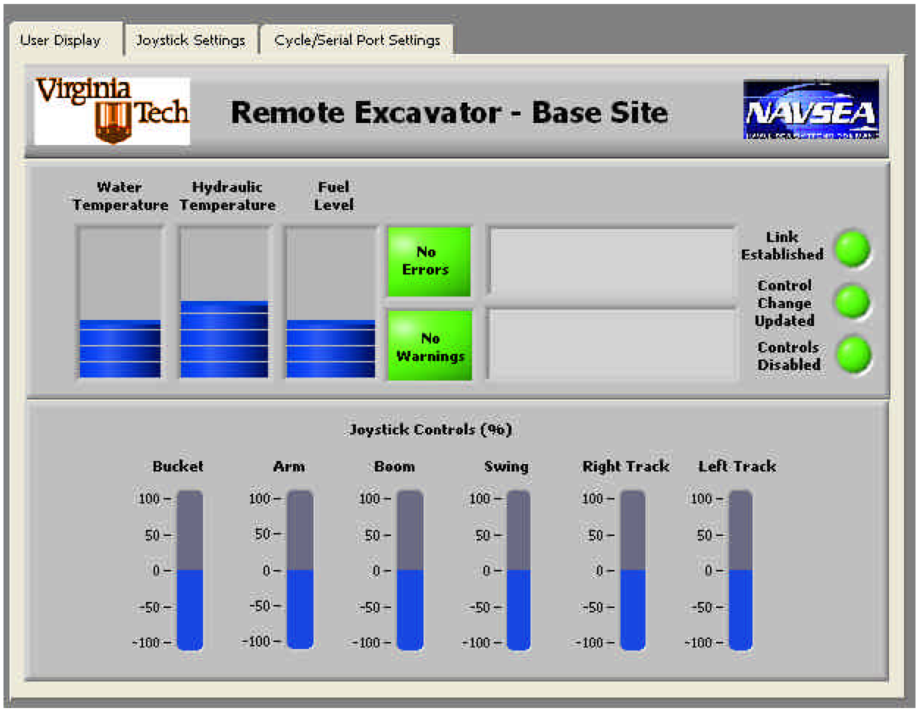

Figure 4-6: Remote operator station user interface

Software. The teleoperated excavator's software was developed entirely in the LabVIEW graphical programming environment. The availability of prewritten device-driver software and LabVIEW's graphical nature provides rapid, modular development of software systems [15].

The software written for the excavator consists of three programs called Virtual Instruments. Each FieldPoint network module executes a real-time Virtual Instrument (VI) when power is applied to the device. The master program is located at the remote station, and the two slave programs are located on the excavator. The first slave manages control decisions and generates operator feedback to the remote site. The second slave provides connectivity with the excavator's onboard computer. The master controls the slaves by sending commands that are imbedded in custom serial data strings over the wireless network. Each program has built in error checking to insure data integrity, and all programs boast failsafe interlocks. These failsafe interlocks assure that in the event of communication loss, the excavator will revert to a safe, suspended motion state. Excavator control decisions can be updated at rates up to 40 Hz.

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Chapter 5 – Detailed Design of the Teleoperated Excavator

The purpose of this chapter is to provide extensive information regarding the design of the teleoperated excavator. While Chapter 4 imparts an abridged version to the overall design solution, this Chapter will provide detailed information of the working characteristics of each subsection of the excavator.

Consistent with the format in the previous chapter, the design analysis will begin by explaining the hydraulic system conversion, offering insight into the conventional operation of the excavator as well as the remotely controlled version. Subsequently, in the electronics section, all components will be described as they relate to the control of the excavator. Finally the discussion of the design will culminate with human factors analysis and packaging considerations.

5.1 Hydraulic System Conversion

The original hydraulic system, which was purely mechanically actuated, had to be modified to enable electronic, drive-by-wire control of the various hydraulic circuits. The excavator is conventionally controlled using mechanical, pressure-controlled joysticks. These joysticks, which operate in the low-pressure pilot system (500-psi), port pressure to the main spool valves. These spool valves supply directional control of the main cylinders (5500-psi). For remote control electronic valves were placed in the pilot system.

Valve options. Two families embody the choices for electronically controlled valves, proportional valves and servo valves. As seen in Table 5-1, there are four main differences between servo and proportional valves: filtration level, accuracy, response time, and cost. Proportional valves do not have pressure feedback, therefore constant load conditions are difficult to maintain. Proportional valves only assure that the calibrated orifice size (pressure drop) is maintained [13]. With feedback, servo valves typically take up more space and require additional electronic and hydraulic components. This increased precision comes at the cost of much higher filtration requirements than the particulate levels seen in conventional construction equipment [13]. The price of servo valves range from $1,000 – 2000, while proportional valves can be found below $200. This is an important decision in the design of a hydraulic system.

Table 5-1: Comparison of characteristics of proportional valves and servo valves [13]

	PROPORTIONAL VALVES	SERVO VALVES
Type of Loop	Open	Closed
Feedback	No	Yes
Accuracy	Moderate Error factor ≅ 3%	Extremely high Error factor < 1%
Cost	Moderate	High
Response	Low: < 10 Hz	Very high: 60 – 400 Hz
Need for auxiliary electronic equipment	Moderate	Substantial
Sensitivity to contamination	Tolerant	Highly

Proportional valves should not be used where precise control is necessary. For applications such as aircraft simulators and other higher speed hydraulic equipment, servo valves are the obvious choice, but for the case of the teleoperated excavator, high precision can be waived for the cost benefit. The teleoperated nature of the project permits some error since operators will be closing the loop with their eyes. An automated excavator would benefit from using servo valves for electronic control.

In order to select the correct electronically controlled valve system, the astute engineer must first consider the location of these valves within the system. All hydraulic equipment systems do not have pilot circuits. However, if a pilot system is present, this is the ideal area to interface an electronically controlled system. One will find that lower pressures offer more design alternatives as well as an increased degree of safety. The next step is to determine flow rates and pressure ranges. This will further narrow the choices of valve systems. Lastly filtration should be considered. Proportional valves typically do not require additional filtration [13]. If a machined manifold is used to plumb these features, filtration is recommended to catch particulates from the newly machined manifold.

Proportional Valves. The proportional valves used on the teleoperated excavator control the main spool valves in the same manner as the original equipment joystick valves. The joystick valves in the cab of the excavator vary pressure output to the spool valves proportionally with respect to their angular rotation from their neutral positions [11]. The proportional valves also vary the pressure to the spool valves; however, they use an electrical signal as their input.

There are six pairs of 3-way hydroelectric proportional valves that provide bi-directional electrical control of all six axes on the excavator (boom, arm, bucket, swing, right track, and left track). The particular valves that are used in this project are model number TS98-31 proportional pressure control valves manufactured by *Hydraforce, Inc.* [12]. These valves operate under pressure ranges and flow rates similar to the conventional joystick valves supplied with the excavator. A symbolic representation of the valve is shown in Figure 5-1. Figure 5-2 shows a cutaway drawing of the same valve. For additional information on symbols seen in common hydraulic schematics consult Appendix A – Hydraulic Symbols.

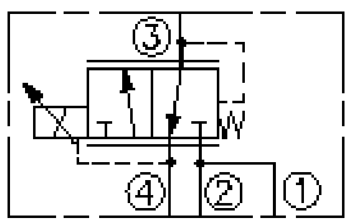

Figure 5-1: Schematic representation of a proportional pressure control valve [12]

In the Figure 5-1, it can be seen that ports 1 and 2 are internally connected. For operation of the valve, supply pressure is run to port 2. The pressure-controlled output line is connected to port 3, and the return line (port 4) is connected to the reservoir tank.

The valve is normally closed, therefore when the coil is not energized, no flow occurs from port 2. As seen in the right box of the schematic, the supply line (port 2) is blocked off, and inhibits flow when the coil is not energized. It should also be noted that when the valve is closed (off) flow is permitted from port 3 to port 4 (the tank line). This allows the excavator's spool valve to shift back to its neutral position.

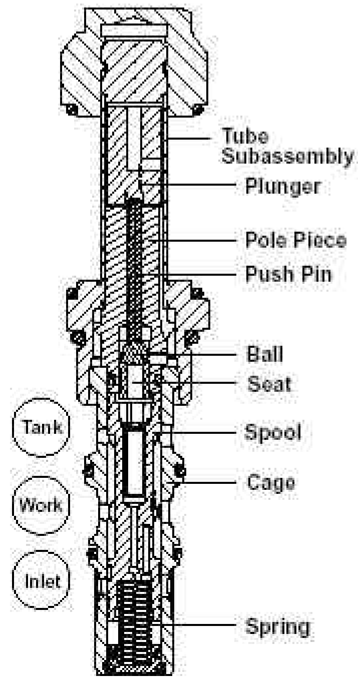

Figure 5-2: Cutaway view of TS98-31 proportional pressure control valve [12]

When the valve is open, flow is no longer permitted from port 3 to 4, rather, flow occurs from port 2 to 3. This flow path is illustrated by moving the center box of the schematic in Figure 5-1 to the right side. The TS98-31 valve allows pressure at port 3 to increase proportionally with the voltage applied to the valve's coil. Changing the calibrated orifice opening varies the pressure drop from the supply line to the output. Small orifice sizes produce a greater pressure drop yielding lower output pressures. When fully opened, the output pressure will be equal to the pressure of the supply line. This allows electronic control of the spool valves as illustrated in Figure 5-3.

The schematic shown in Figure 5-3 operates the Case CX-160 Excavator; however it eliminates the conventional in-cab controls. In order to include these controls, shuttle valves are added to create a system of parallel controls.

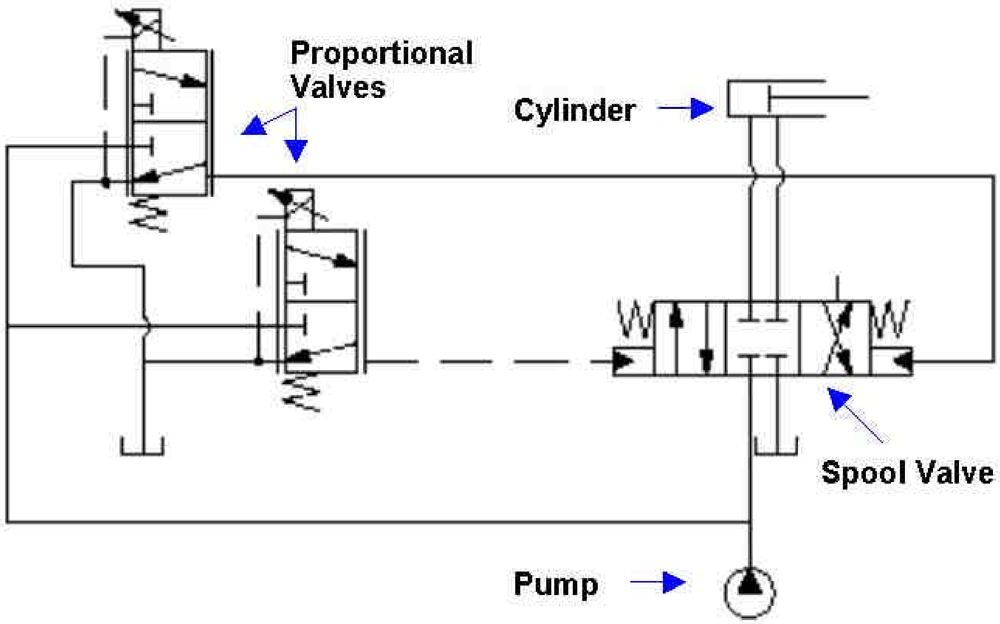

Figure 5-3: Two proportional valves controlling a stack (spool) valve as in the CASE CX160 excavator

Shuttle Valves. A shuttle valve permits control of the excavator's main spool valves via either the conventional joystick or the electro proportional valve. Figure 5-4 shows that flow from either end will push the ball across the chamber and block flow from the opposite end. When shuttle valves are plumbed into the system as shown in Figure 5-5, the spool valve can be controlled by whichever control (conventional or electro-proportional) is outputting the highest pressure.

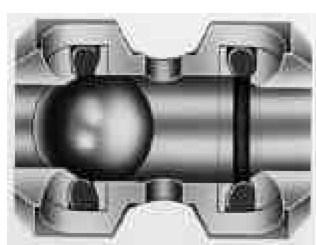

Figure 5-4: Shuttle valve [17]

Depicted in Figure 5-5, is one circuit of the excavator's six control circuits and the modifications that were made. A manifold was constructed to house the 12 proportional and 12 shuttle valves. This manifold reduces hoses used in the system, and creates a more compact installation of the components. In Figure 5-6 the manifold with the 12 proportional valves can be seen. At first glance, the design may seem messy, but the use of a manifold eliminated the need for

24 additional hoses. Supplementary filtration was added to the system to catch particulates in the early stages of operation. This filter is a *PTI Technologies* model number F1L-025 hydraulic filter [18].

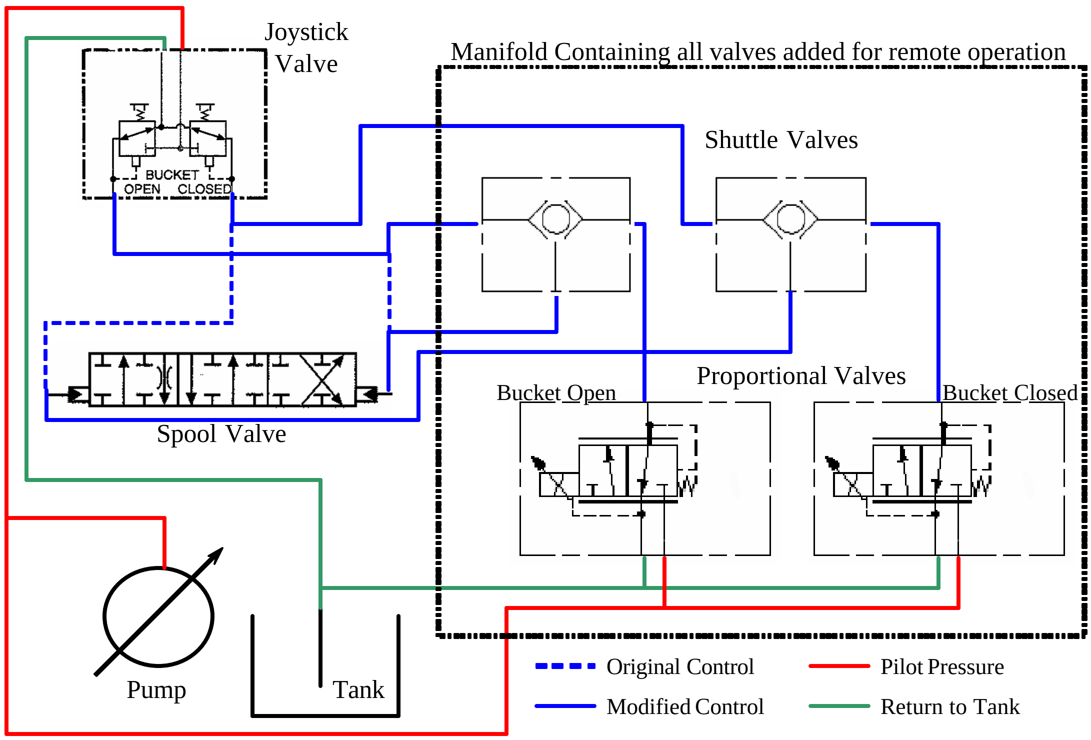

Figure 5-5: Schematic depicting one of six circuits to control the excavator [Hovey]

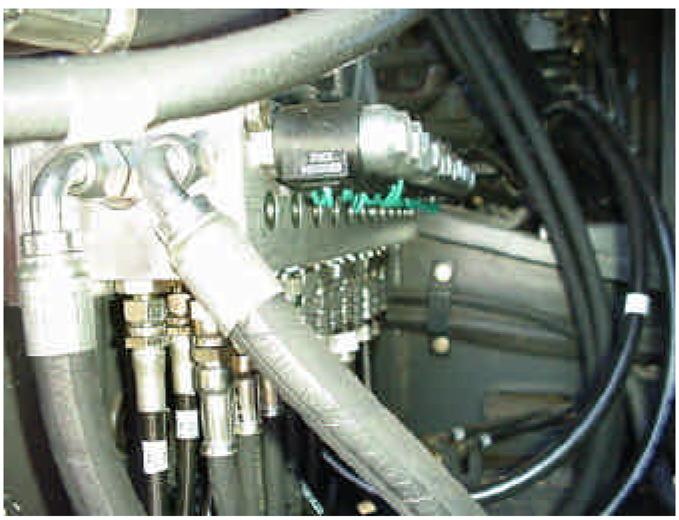

Figure 5-6: Picture of manifold with proportional valves installed

5.2 Electronic Modifications

The electronics that make up this system consist of two distinct parts, excavator side components and remote operator station components. These two separate systems communicate via radio transmission in both the 900 MHz and 2.4 GHz band. The components added to the excavator are listed below in Tables 5-2 and 5-3.

Table 5-2: Excavator side components

Qty.	Part
2	*National Instruments* FP-2000 network modules
2	*National Instruments* RLY-420 relay module
2	*National Instruments* AO-210 analog voltage output modules
12	*HydraForce* proportional valve controllers
12	*HydraForce* proportional hydraulic valves
1	*TrippLite* 400W (24V) inverter
1	12 VDC regulator
1	Pan/Tilt motor (AC)
3	CCD cameras (2 with integrated sound)
3	Audio and video transmitters (2.4 GHz)
1	*Data-Linc* SRM6000 900Mhz radio modem (slave)
1	*Futaba Industrial Radio Control* VSD-2002 (E-Stop receiver)

Table 5-3: Remote operator station components

Qty.	Part
1	*National Instruments* FP-2000 network module
1	*National Instruments* DI-300 discrete input module
1	*National Instruments* AI-100 analog voltage input modules
2	Dual axis *Suregrip* joysticks
2	*P-Q Controls* industrial single axis foot pedals
3	Audio and video receivers (2.4GHz)
1	*Data-Linc* SRM6000 900 Mhz radio modem (master)
1	*Futaba Industrial Radio Control* VSD-2002 (E-Stop transmitter)

Radio Modems. The excavator and remote operator station are linked by *Data-Linc* SRM6000 serial radio modems (Figure 5-7). This device operates a frequency hopping spread spectrum algorithm in the 900 Mhz band. Frequency hopping is a radio data transmission technique common to existing wireless communication media with protocols similar to Blue Tooth or the IEEE 802.11 standards [19]. Transmitting for a short time on a single frequency decreases the possibility of interference, which helps maintain data integrity and increases signal-to-noise ratio.

Although similar in many ways to commercially available wireless LAN media, the SRM-6000 has distinct differences. First, it does not conform to any IEEE standards [16]. The SRM6000 employs its own hand shaking and 32-bit CRC error correction. This device can serve up bi-directional serial data streams at throughput rates from 1.2 to 115.2 kbps. The SRM6000 can operate at ranges of up to 20 miles line-of-sight, depending on environment, geographical conditions and antenna. Network security is mediated through a modified version of the Dynamic Host Configuration Protocol (DHCP), which involves device specific Media Access Control (MAC) numbers. The addition of this device to the teleoperated excavator further assures that critical control information will reach the excavator promptly.

Figure 5-7: SRM 6000 radio modem [16]

Safety system. As stipulated in the design requirements, the teleoperated excavator must have a completely separate emergency stop system. A *Futaba Industrial Radio Control* VSD-2002 long-range telecontrol system provides emergency stop control at a range of up to 2 miles [20]. This device is similar to the radio modem, whereas the VSD-2002 also employs a frequency hopping spread spectrum algorithm in the 900 MHz band. However, this device serves only to relay the status of switches attached to the transmitter. Relays on the receiver are directly connected to the excavator's original emergency stop relay. The separate, reliable system insures that a malfunctioning excavator will not cause harm to itself or any human. An additional part of the safety system is a yellow, flashing light located on the top of the excavator cab. This light will flash when the operator enables the remote controls, thus indicating to anybody in the immediate area to take caution.

5.2.1 Excavator side electronic components

Power System. All components on the excavator side are powered directly by the onboard +24 V battery. A fail-safe, high-current relay permits power to flow to all components. Electronic components inside the excavator side control box are protected by ¼ x 1¼" fast acting glass fuses. Noise on the power input reduced by two 3300μF capacitors that are located just after the high power relay, which reduce the 1.5-V peak-to-peak noise floor down to 200mV peak-to-peak. When the pan and tilt module (AC drive) is in operation, the inverter is turned on, and additional noise climbs to 600 mV-pp. All electronic components have internal voltage regulation, and they will reject the increased noise. A robust 10-A, 12-VDC voltage regulator delivers power to sensitive components such as the audio/video transmitters, the emergency stop and the radio modem. Although FieldPoint devices are sensitive, they must have input voltages above 13 V, so the 12VDC regulator does not power these devices.

For any application where modifications are made to a stock vehicle, existing power consumption constraints of the stock alternator should not be violated. As seen in Table 5-3, the excavator has an onboard alternator that can handle up to 45 amps. Analysis with a current clamp demonstrated that during normal operation 11.5 amps current draw is expected.

Table 5-3: DC Current analysis of the teleoperated excavator

Device	Current Draw (A)
Alternator Rated Output	**45.0**
Target max continuous load on system (75% alternator rated output)	**33.8**
Lights	5.0
Enable pilot controls	0.5
Climate control fan	6.0
Engine Idling, all accessories turned on except windshield wipers	19.2
Engine Idling, accessories necessary for remote operation only (lights)	**11.5**
Immediately after start battery draw for a few seconds (cold start)	40.0
Proposed max current draw from valves	**10.5**
Reserve current for additional electronics (excluding valves)	**23.3**

In order insure that the alternator is not over tasked, the team decided that the power consumption of stock equipment and additional electronics should not exceed 75% of the alternator's capacity at any time. Therefore, maximum draw on the alternator should not exceed 33.8 amps. All additional electronic components were verified to be within the 22.3 amps range for any type of operation. However, for a cold start-up it was recommended to NSWC not to utilize the remote start function, because the alternator could be overtaxed. Immediately after the engine is cold started, current draw from the original equipment is expected to reach 95% of the alternator's capacity.

FieldPoint. The *National Instruments* FieldPoint (FP) modules are the backbone of the teleoperated excavator (Figure 5-8). FieldPoint is a real-time distributed I/O system and boasts excellent connectivity and reliability. These devices (FP-2000, RLY-420, AO-210) are located within the excavator side control box.

Figure 5-8: FieldPoint modular distributed I/O system [15]

The FP-2000 network module runs a real-time LabVIEW operating system. An embedded Virtual Instrument (VI), which is a software component written in LabVIEW, will begin execution when power is applied to the device [15]. The FP-2000 communicates with other modules on an inline bus, and it also can communicate with other FP-2000 modules through either the 10/100-ethernet ports or the serial (RS-232C) port located on its exterior. There are two FP-2000 devices located within the excavator control box. The main network module receives and transmits information to the remote station via the serial port, and performs excavator control tasks through modules located on an inline bus. The secondary FP-2000's serial port connects to the *Sumitomo* ECU seen in Figure 5-9, via RS-232C serial communication port. The *Sumitomo* ECU outputs a serial data string containing information such as oil temperature, water temperature, fuel level, and warning messages This secondary FP-2000 relays this information to the main network module through a network Datasocket packet [15].

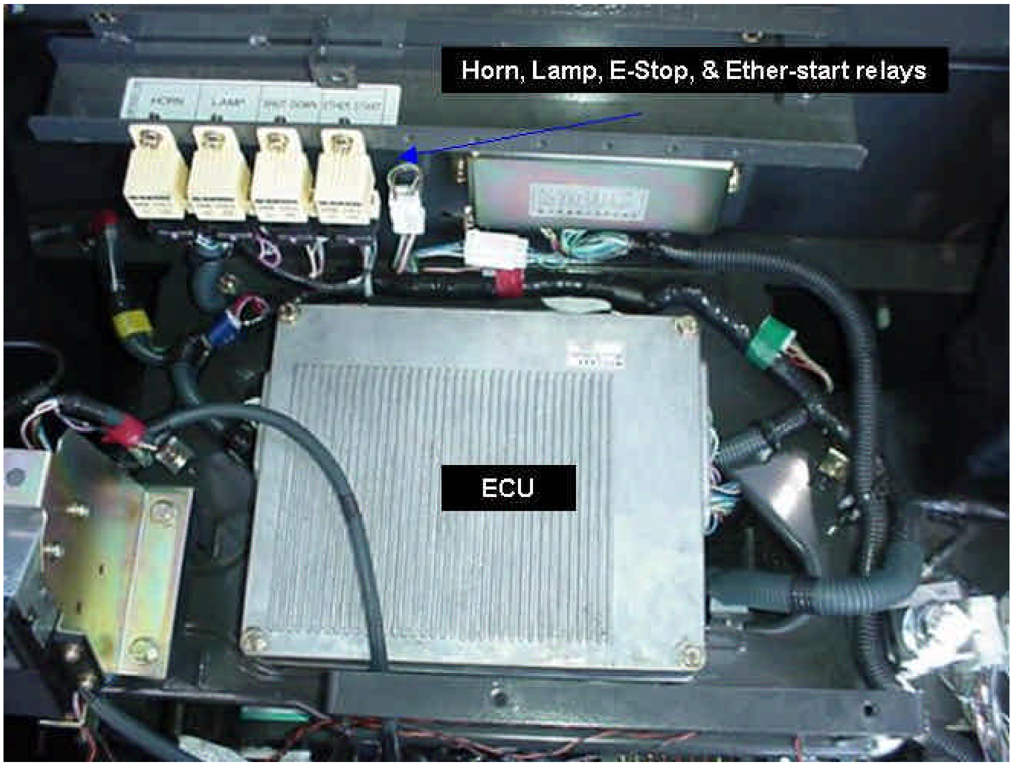

Figure 5-9: *Sumitomo* original equipment ECU

The two RLY-420's relay modules are the means for controlling discrete events on the excavator. These devices are powered via the inline bus from the main FP-2000 network module. The first relay module, controls the starting and stopping sequence of the excavator's engine. Also, this relay module controls a yellow flashing light that indicates that the remote side controls have been enabled. Lastly, this first module allows the operator to turn off/on the audio/video transmitters. This feature was added to provide time to transfer heat from within the box prior to powering the audio/video transmitters. The second RLY-420, controls all of the pan and tilt functions. These functions are separated, because the pan and tilt requires an AC source. The flow of information on the excavator side can be seen in Figure 5-10.

The 6 axes of the excavator are controlled through the two analog output modules (AO-210). These devices output a voltage between 0 and 5 volts, which serves as a control voltage for the *Hydraforce* valve controllers.

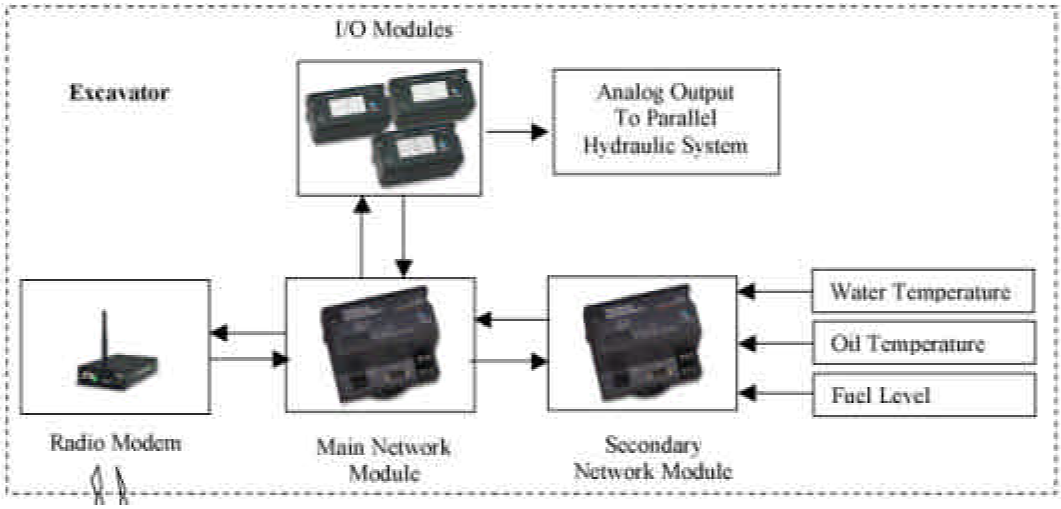

Figure 5-10: Excavator side FieldPoint component information flow

***Hydraforce* Valve Controllers.** The *Hydraforce* valve controllers output a pulse width modulated (PWM) signal with amplitude of 20V. The duty cycle of the PWM signal is proportional to the reference voltage. Control parameters such as the output signal's ramp time as well as dither frequency and dither amplitude are adjusted directly on the controller with a potentiometer [12]. Care must be taken in adjusting these gains. Incorrect gains can add adverse dynamics to the hydraulic system that may cause ringing or instability [22].

Vision system. The excavator is equipped with three CCD video cameras. The first camera, located on the pan/tilt//zoom drive, is the main camera. The focal length of this camera can be changed, but it is currently set to 7mm. The field of view extends past the bucket, while providing vision information closer to the tracks.

The second camera is a wide-angle camera that can be manually positioned and locked into place. This camera is normally positioned downward enabling the operator to visualize the orientation of the cab with respect to the tracks. This is important, because the excavator bucket can strike the tracks if brought too close. The excavator is less stable in operation where the boom is perpendicular to the tracks and, driving the tracks requires the operator to identify their location with respect to the cab. The final camera faces the rear of the excavator, aiding in backing up as well as gaining a reference of where the excavator is located on the dig site.

Telemetry. Located on the excavator are five antennae. The first is a large *Maxrad* 3dBi antenna that has been tuned for operation in the 900 MHz range. This antenna is used for the radio modem, and is connected to the SRM6000 by low loss outdoor coaxial cable. The next antenna is the stock antenna provided by the *Futaba* VSD-2002 emergency stop radio modem. The remaining three antennas are 2.4 GHz rubber ¼-wave whip antennas that serve as the audio/video transmission link.

5.2.2 Remote operator station electronic components

The remote control site consists of all components that the operator accesses while performing teleoperated control. The operational distance is limited to 3000 feet by the range of audio/video transmitters. This section will detail the flow of information within the electronic components located at the remote operator's station.

FieldPoint. Located at the remote operator station are three *National Instruments* FieldPoint modules. These modules consist of a FP-2000 network module, a DI-300 discrete input module, and an AI-100 analog voltage input module. The flow of information between these devices at the remote operator station can be seen in Figure 5-11, which also includes the components from the excavator side.

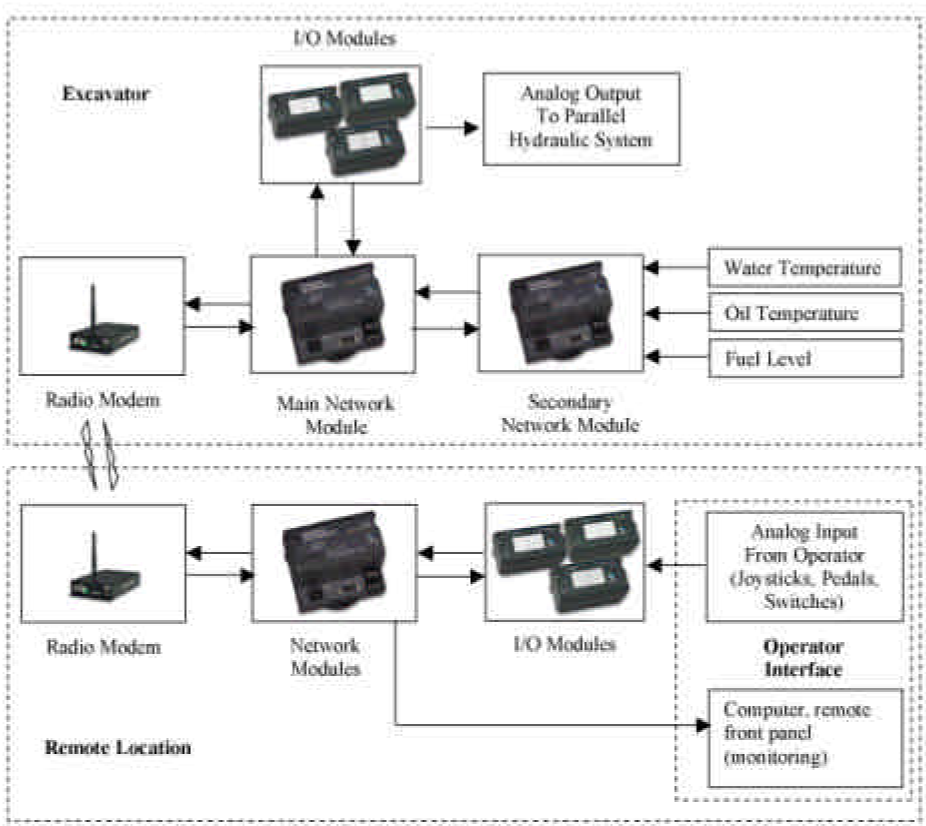

Figure 5-11: Wireless distributed I/O system

An embedded VI on the FP-2000 network module controls all of the data into and out of the operator's station. The serial port on the FP-2000 connects to the master SRM6000 radio modem, and the ethernet port connects to a network hub. A computer on the network monitors the front panel of the embedded VI. The FP-2000 inline bus connects to the remaining two FieldPoint modules. On the inline bus are the DI-300 and the AI-100 modules. These modules supply all inputs from the operator to the teleoperated control system.

The AI-100 analog input module reads reference voltages that serve as the input for control of the excavator's six degrees-of-freedom. Attached to this module are two dual-axis joysticks and two foot-pedals. The module can sample all six axes 400 times per second (400 Hz, 2.5ms/sample). However, the software embedded on the FP-2000 determines the rates at which these control signals are sent to the excavator. The original control interface and remote interface joysticks can be seen in Figure 5-12.

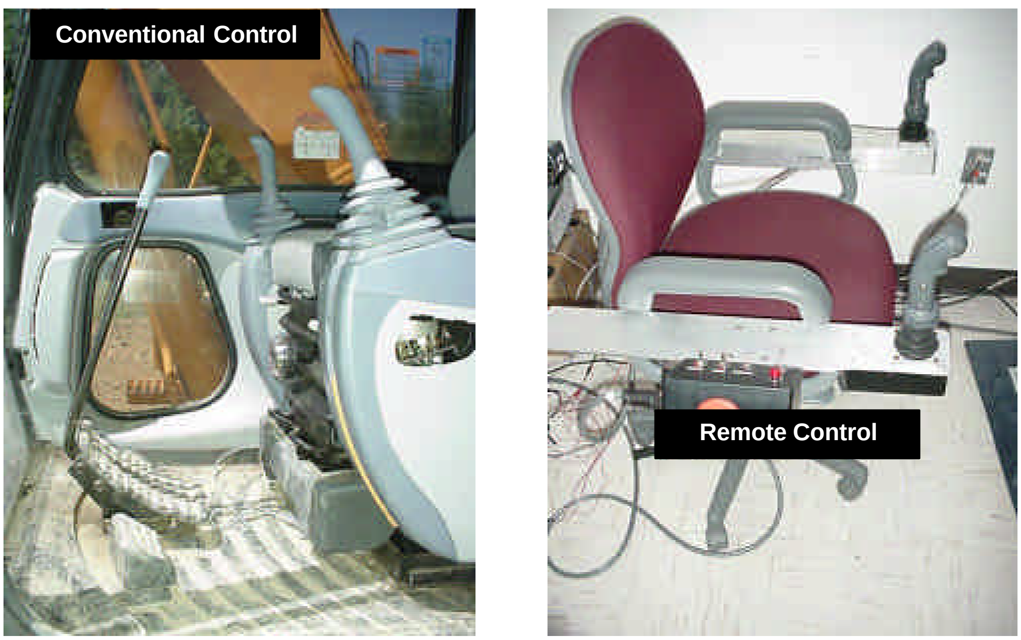

Figure 5-12: Conventional and remote excavator control joystick interfaces

The DI-300 discrete input module allows the operator to perform various actions by actuating switches on the control box located the operator chair Figure 5-13. From this control box, the operator can power in-cab accessories, start the engine, and enable remote control. A large emergency stop switch is also located on the control box. This switch is directly connected to the emergency stop transmitter.

Figure 5-13: Picture of remote operator control box

Joysticks and Foot Pedals. The *Suregrip Controls* joysticks are dual-axis, Hall effect, analog output devices. They require a 5-VDC input, which will serve as a reference signal. At top-dead-center, the joysticks will output 2.5 volts, and rotation about the center position produces output voltages of 80 and 20 percent of the reference voltage at the extents. These joysticks also have rocker switches that control the pan and tilt of the excavator's main camera. The *PQ Controls* foot pedals are potentiometer based analog output devices. The foot pedals will output a voltage proportional to the input voltage.

Operator Interface. The operator interface, which was discussed in the previous FieldPoint section, is a monitoring device for the operator (Figure 5-14). The computer must have LabVIEW or a LabVIEW runtime engine installed to view the VI. Once installed, the front panel of the VI can be viewed by directing a web browser to the IP address of the network module. This interface allows the operator to view the excavator's fuel level, oil temperature, water temperature, and any error or warning messages. Six slider indicators show the status of all six axes of control input (joysticks and foot pedals. Also on this operator interface display is an indicator of the status of communication between the remote site and the excavator via the radio modems. These indicators are feedback from the fail-safe software interlocks.

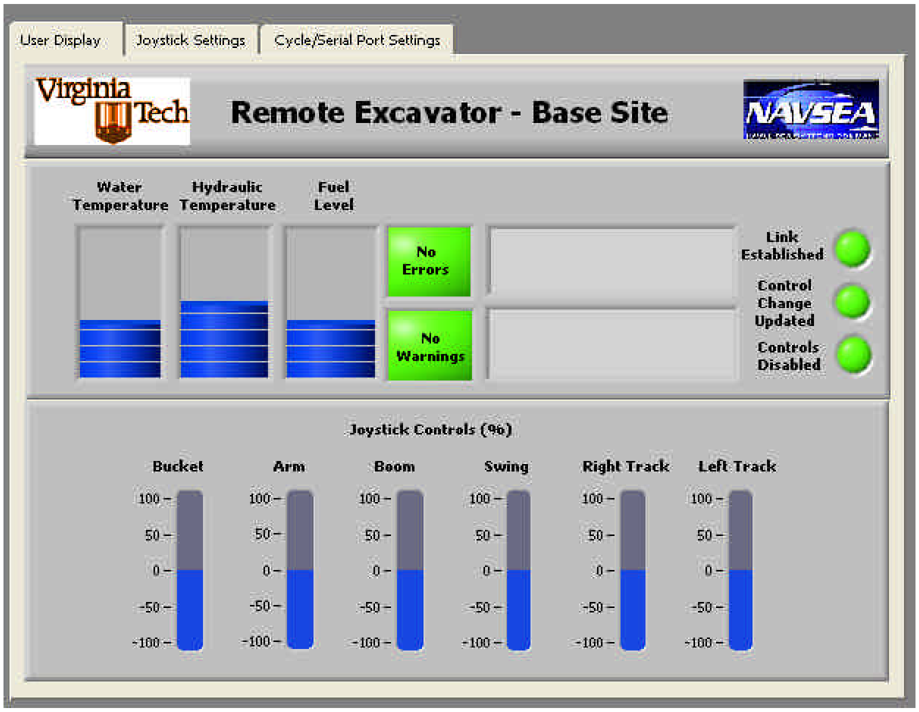

Figure 5-14: Remote operator interface

Audio/Video Interface. The audio/video receivers located at the remote operator's station operate at a range of up to 3000 feet line-of-sight. Transmitting in the 2.4GHz band, the transmitters are highly susceptible to interference, because they do not use a frequency-hopping algorithm similar to the radio modems.

5.3 Human Factors Considerations

Operating a 16-ton Excavator remotely through the use of video cameras is difficult. Regardless of the amount of effort devoted to replicating the original controls, control will feel different. This difficulty embodies the fundamental problem in teleoperated robotics. In an effort to improve remote operation, robotic systems are designed to minimize operator inputs. Increasing the level of autonomy in teleoperated systems is not an act of laziness. Rather, it is due to the need for increased productivity.

The goal of this project did not include autonomous operation; therefore, an effort to understand human factors at play on the machine was performed. Operating construction equipment efficiently requires many hours of experience. In much the same way as one drives a car, vision, sound and "feel" play an important role in understanding how the excavator is performing. The roll and pitch of the cab as the manipulator digs is a performance indicator. Simple teleoperated systems typically do not have force-feedback at the remote operator station.

In order to determine the level of efficiency that could be provided with a simple teleoperated system, preliminary "black-box" tests were conducted. The excavator cab was blackened and a television was installed inside the cab. It was found that operating the excavator with only one camera was extremely difficult, however after hours of testing efficiency was improved through operator adaptation. With only one camera depth perception is difficult, and it is necessary reference known objects in the frame of view to understand depth and size. Additional cameras or stereovision can help regain some depth perception.

While stereovision offers a much better perception of depth, multiple cameras were selected for cost benefits and design time tradeoffs. Through testing and training, the operator efficiency was not greatly affected by the lack of depth perception. The lack of force feedback also did not adversely affect operator performance. The cameras were fixed to the area of the excavator that would normally experience the pitching and rolling, and the operator was able to retune and redirect force feedback senses to monitor the movement of the video image.

Designing the remote operator interface also required a look at human factors. Although there would be no force feedback in the joysticks, stiffness comparable to that of the mechanical in-cab joysticks was selected. The locations of those joysticks on the chair were made adjustable to increase operator comfort. Replicating the exact look and feel of the in-cab controls did not need to be exact; rather, it needed to be comfortable. The tedious nature of the work being performed required any additional controls be at an arm's reach. The emergency stop and the ignition sequences are located directly on the chair. The operator can change camera views without removing his hands from the joysticks. Two large television screens and an LCD projector ease the strain on his eyes.

The on-screen user interface is designed for a person with very limited computer knowledge. The user display that provides fuel level, water/oil temperature, and any warning messages can be accessed through any web browser. Limiting the need for mouse and keyboard inputs allows the operator to concentrate on the task at hand and minimize fatigue.

While the teleoperated interface does not provide all the feedback experienced on-board the excavator, the performance experienced by the operator indicates that some of the feedback may not be necessary. Should any additional information be necessary, simple software changes can be made. A comfortable and customizable interface allows the operator to work efficiently, and through training and adaptation, performance can be increased.

5.4 Packaging Considerations

Customer requirements stipulated that the teleoperated system had to withstand outdoor elements. The size of the excavator requires it to always be located outside, and the location on the Potomac River will subject the machine to a wide variety of weather conditions. In addition to weather constrains the system must be portable as well as easy to set up and maintain.

The space-limited interior of the excavator cab required additional electronic components to be mounted outside above the cab. To protect these components a NEMA-4 rated box is employed, which resists all weather elements. A louver and air filter system in conjunction with DC fans rejects heat from the electronic components, while preventing moisture from entering the enclosure. An aluminum shield above the box minimizes addition of solar heat (Figure 5-15). On a sunny day with exterior temperature of 95°, the interior of the box is lowered by 8 degrees. The three cameras are protected by outdoor camera housings.

Figure 5-15: NEMA-4 rated electronic enclosure

This concludes the detailed design of the teleoperated excavator. For any additional information about specific subsections of the design, the interested reader should consult cited references.

Chapter 6 – Testing and Performance

Due to the limited design timeframe of the project, rigorous testing standards in industry were not employed. However, through the use of off-the-shelf components the design is expected to be durable and easily serviced. The excavator has endured 10 months of exposure to the elements, which included a very hard winter and also has experienced over 50 hours of teleoperated use.

6.1 Predicted Performance

The initial testing phase conducted before delivery focused mainly on putting the software system through its paces. Through numerous revisions, a stable reliable software control system is in place. The failsafe interlocks function correctly, and control of the excavator is smooth and relatively free of delay.

Also in the early stages of the design, black box testing was performed on the excavator to understand how much an operator would rely on force-feedback and depth perception. Early in the design, tests were performed with a skilled operator on the teleoperated system. After one hour of teleoperated control, the operator claimed that he could operate at 50% efficiency. Through system improvements and training that capacity has been raised to 80%. It is difficult to exactly replicate control in a teleoperated application, and marinating efficiency requires the operator to learn and adapt to the new set of inputs and outputs.

As seen in Table 6-1, through testing, the wireless operation range extends up to 3000 feet. Implementing higher power video and audio transmitters can extend this range. However, the teleoperated excavator can be operated anywhere in the world via the Internet without loss in control update rates. This is not recommended unless a high-speed video feed can be established. As mentioned previously, operator efficiency has been increased to 80% through testimonials of skilled operators. It is believed that through the use of systems such as stereovision and force-feedback this capacity can be increased further.

Through excellent data throughput rates software control can be updated at speeds up to 40 Hz, however the frequency response of the hydraulic proportional valves limit the control of the excavator's six degrees-of-freedom to 10Hz. This rate is acceptable due to the slow dynamics of the excavator itself.

Table 6-1: Teleoperated excavator performance

Operation range	3000 ft
Operator efficiency	80%
Actuator control update rate	10 Hz
Software control update rate	40 Hz
Operating temperatures	20° - 130°F

6.2 Hydraulic System Modeling and Analysis

Upon installation of the parallel hydroelectric control system, all axes seemed to perform very well. Operators experienced little differences between conventional controls and remote controls. However, after further testing problems were found in the bucket circuit. This circuit experienced a moderate vibration upon actuation of the remote controls only. Over time, this ringing has increased in amplitude, but frequency has remained the same. An exhaustive analysis to determine the cause of this effect is currently underway, and a definitive solution has not yet been ascertained.

Preliminary Efforts to Remove Vibration. As mentioned, the vibration has increased over time, but the temperature of the hydraulic oil greatly affects this vibration. So, it cannot be assumed that the problem is getting worse in time. Since initial tests were conducted in the heat of the summer, it is believed that the vibration could reduce during summer months. But, this is not a solution. The hydraulic design must work in all times of the year. The following discussion will present the process taken by the design team to remove this vibration.

The team set out to determine if there were any defects in the materials or components in the hydraulic system. The first step was to insure that all valve controllers and valve solenoids were operating correctly. By switching controllers and cartridge valves on the manifold, it was determined that there were no defects in these components. Second, the manifold was run through a CMM to determine if all of the bore diameters were within specifications. Next, the bucket circuit's spool valve hoses were placed on a different location on the manifold, and the same vibration was experienced. This led the team to believe that there were no mechanical defects in the parallel hydraulic system. Due to the fact that conventional, in-cab control of the bucket was free of vibration, the original equipment was not examined for defects.

Ruling out mechanical defects, understanding if there were dynamic issues at play needed to be addressed. The team turned to the original equipment hydraulic schematic to understand the fundamental differences between the bucket circuit and the other 5 axes within the pilot circuit. It was determined that the bucket circuit was unique. The manufacturers had designed this circuit to have the highest sensitivity possible.

While circuits such as the boom and arm had cushioning systems, the bucket circuit did not. Also, the bucket circuit is unique because it does not have any throttling valves before the spool. Throttling increases flow velocity, which by Bernoulli's equation reduces pressure across the orifice [23]. So, it can be expected that the bucket spool could experience the full range pilot system pressures while other axes may not. This alone did not lead to any other conclusions or solutions about how to fix the vibration, rather it just proved that there may be similar effects in the other circuits and the effects are not being seen. It is possible that the larger inertias of the other circuits may be attenuating vibration in these subsystems.

Regardless, of how the other circuits were operating, the vibration had become so severe that operation of the machine had to cease. The bucket circuit was re-plumbed in an orientation that bypassed the manifold. This apparently solved the problem, although the maximum speed possible was reduced. Digging was able to commence, but true cause of the problem had still not been ascertained. It is believed that the bypass circuit detuned the vibration, but the specific part of the bypass that detuned it has not yet been fully understood.

A pressure perturbation in the pilot system between the spool and proportional valve could be the only cause of vibration on the bucket. The spool would have to be translating along the stroke axis at a frequency proportional to the low frequency vibration seen in the bucket. After consulting with *Hydraforce*, the proportional valves were bled to eliminate any possible trapped air in the system [24]. Unfortunately, the bleeding efforts did not solve the problem.

The team considered the addition of an accumulator before the manifold. This has not yet been implemented, but when in place, the accumulator will help to maintain a constant pressure at the input to the proportional valve. Pressure readings will be taken at the input and output of the proportional valve to determine if the accumulator in fact helped attenuate the pressure perturbation. However, without data or engineering calculations, this may not solve the problem. Modeling the system dynamics at play will yield the only true cause of the vibration.

Bucket Pilot System Modeling. Oil is the chosen medium used to convert fluid power energy to mechanical energy in common hydraulic equipment. Often, in fluid power circuits, the medium is considered incompressible. Although very difficult, all fluids can be compressed, and this compressibility adds dynamics to the system [23].

Modeling the hydraulic system affecting the bucket begins by drawing a free body diagram. The free body diagram can be seen in Figure 6-1, but this can be simplified further. As seen in Figure 6-2, the system can be simplified into a two-mass system with stiffness connecting them if the mass of the spool, M_s is neglected.

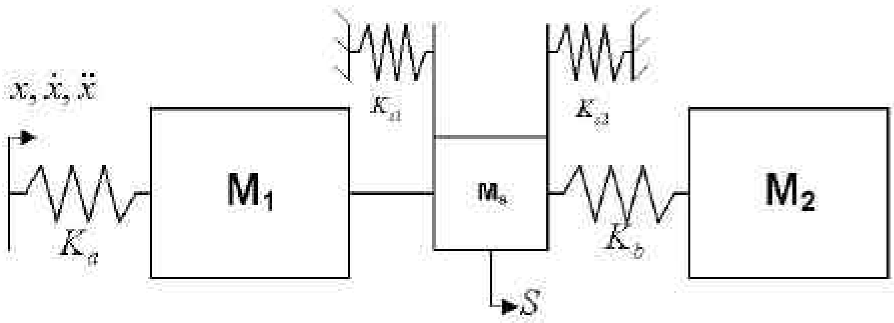

Figure 6-1: Free body diagram of bucket pilot circuit

The system can be assumed to be undamped. Between the masses the equivalent stiffness, K_s ($K_s = K_{s1} + K_{s2}$) is the equivalent stiffness of the spring that centers spool valve. The control volumes on each side of the spool make up the two masses seen in Figure 6-2. If the system were incompressible, the stiffness of K_a and K_b can be assumed to be zero, however for this analysis this is not assumed. The values of K_a and K_b are the stiffness of the fluid trapped on either end of the spool valve. These stiffness values can be directly related to the volume of trapped fluid volume and the bulk modulus [22]. Volume is related to the stroke, S, the effective cap-end area of the spool, and the hose length and diameter.

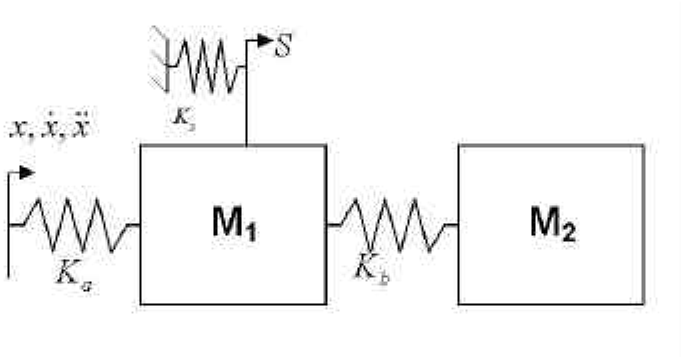

Figure 6-2: Simplified free-body diagram of bucket pilot circuit

If the input acceleration, $\ddot{x}$, is kept below an acceptable level, the mass will follow the input, x. Otherwise, the mass will lag, and ringing will be experienced [25]. The stiffness of a fluid can be determined from the following calculations [22]:

$$V_O = (A_P L_1) \quad (1)$$

$$K = \frac{(A_C{}^2 b)}{V_O} \quad (2)$$

Equation 1, represents the original control volume, V_O, within the hose, where A_P is the area of the pipe or hose, and L_1 is the length of the pipe. Equation 2 is the stiffness of the fluid, K. Stiffness is related to the area of the cylinder cap, A_C, the volume V_O, and the bulk modulus, β. The bulk modulus of a fluid is the measure of the change in volume that occurs when pressure on the fluid changes [22], [23].

The free-body diagram presented in Figure 6-2 is oversimplified, because the equivalent stiffness will change with stroke length. This analysis is concerned with the overall worst-case stiffness (smallest value), and this occurs when volumes on each side of the spool are equal. As stiffness decreases, the natural frequency also decreases making the system prone to ringing from high accelerations [22].

$$C_{MIN} = C_1 + C_2 \qquad at\, stroke length, S/2 \quad (3)$$

$$C_{MIN} = \frac{(A_C{}^2 b)}{(2V_O + A_c S)} \quad (4)$$

$$w_o = \sqrt{C_1 / M + C_2 / M} = \sqrt{C_{MIN} / M} \quad (5)$$

In equations 3-5, the natural frequency ω_o is calculated from the minimum stiffness, C_{min} and the moving mass, $M = w/g$ [22]. From a theoretical view, the natural frequency, ω_o can now be used to calculate the usable acceleration range. However, other capacitances of the system (e.g. hoses, mechanical components, etc.) should be considered. Therefore the usable natural frequency can be estimated as $\omega = \omega_o/3$ rad/s.

The ultimate goal of this controls analysis is to determine a maximum ramp time, or acceleration that will be free of an oscillatory response. The time constant, $\tau = 1/\omega$, is the period required for one oscillation. For stable acceleration, at least 4 to 6 times the period required for oscillation should be allotted, as seen in Equation 7 [22]. This allows for quick estimation of ramp time, and ramp time can adjusted directly on the proportional valve controller.

$$t_{ramp} > \frac{6}{w} = 6t \qquad (7)$$

With maximum ramp determined, the team should be able to understand if the vibration in the bucket circuit is due to lack of stiffness in the hydraulic fluid. Since the currently set ramp times are set at acceptable rates, the system may need to be stiffened to allow for these higher accelerations. If this is the case, the system can be stiffened in two ways.

The first method would be to introduce throttling valves into the system. These valves would operate similar to the bypass circuit. Throttling would produce a pressure drop, which would limit the acceleration of the fluid. However, limiting pressure reduces the maximum stroke distance, which in turn will limit the slew rate of the bucket cylinder. The second, preferred method of stiffening the system requires a reduced control volume. Smaller diameter hoses could be placed between the proportional valves and the spool, effectively increasing stiffness and bandwidth.

While this may not solve the vibration problem experienced in the bucket circuit, understanding the dynamics of any control system is valuable. Common practice is to estimate dynamics, and this can be a dangerous practice when the dynamics involve a 16-ton excavator.

Chapter 7 – Conclusion

Automation of hydraulic equipment has far-reaching economic potential. Throughout this document, a method is demonstrated for equipping an excavator with remote control capability. The excavator can be operated wirelessly at ranges up to 3000 feet, and through the Internet, the excavator can be operated anywhere in the world. Developed by seven Virginia Tech students, a fully functional solution was developed and delivered to the United States Navy for under $20k and in less than six months (Figure 7-1).

Figure 7-1: CASE CX160 excavator and project members

The teleoperated excavator will be a valuable aid in remediation of unexploded ordnance; however, the teleoperated excavator finds use in any application where operator safety is a concern. Making a home in the dirty and the dull, the dangerous and the difficult, teleoperated robotic systems will continue to proliferate through today's marketplace, because the market demands them.

Throughout this project the team was constrained by both time and costs. These constraints helped drive the generation of an extremely cost-effective product. Through readily available commercial products, the teleoperated excavator can be very quickly replicated and upgraded. Little additional design and construction time is necessary to put this solution into motion on another excavator. The teleoperated excavator can be used in as many ways as the original equipment. Additionally, the remote control system can be implemented on any hydraulic system with very few design changes. This asserts that the design has far reaching economic potential.

At a relatively low cost, many branches of the military and countless companies could benefit from equipping existing hydraulic systems with remote control capability. Construction equipment manufactures can offer customers a remote controlled version of their existing equipment for little extra cost. Also, a remotely controlled version of their equipment can replace a human on the test track, where operators have spent countless back-braking hours. The platform developed in this research has potential for becoming a launching point for the production of more intelligent hydraulic equipment.

Consistent with the vision of the Joint Robotic Program, this research aspires to become a "catalyst for the insertion of robotic systems" into the current economic climate [3]. While millions have been spent on similar teleoperated systems, the cost-effectiveness of the solution presented herein affirms the economic potential for the development of these systems in today's economic marketplace.

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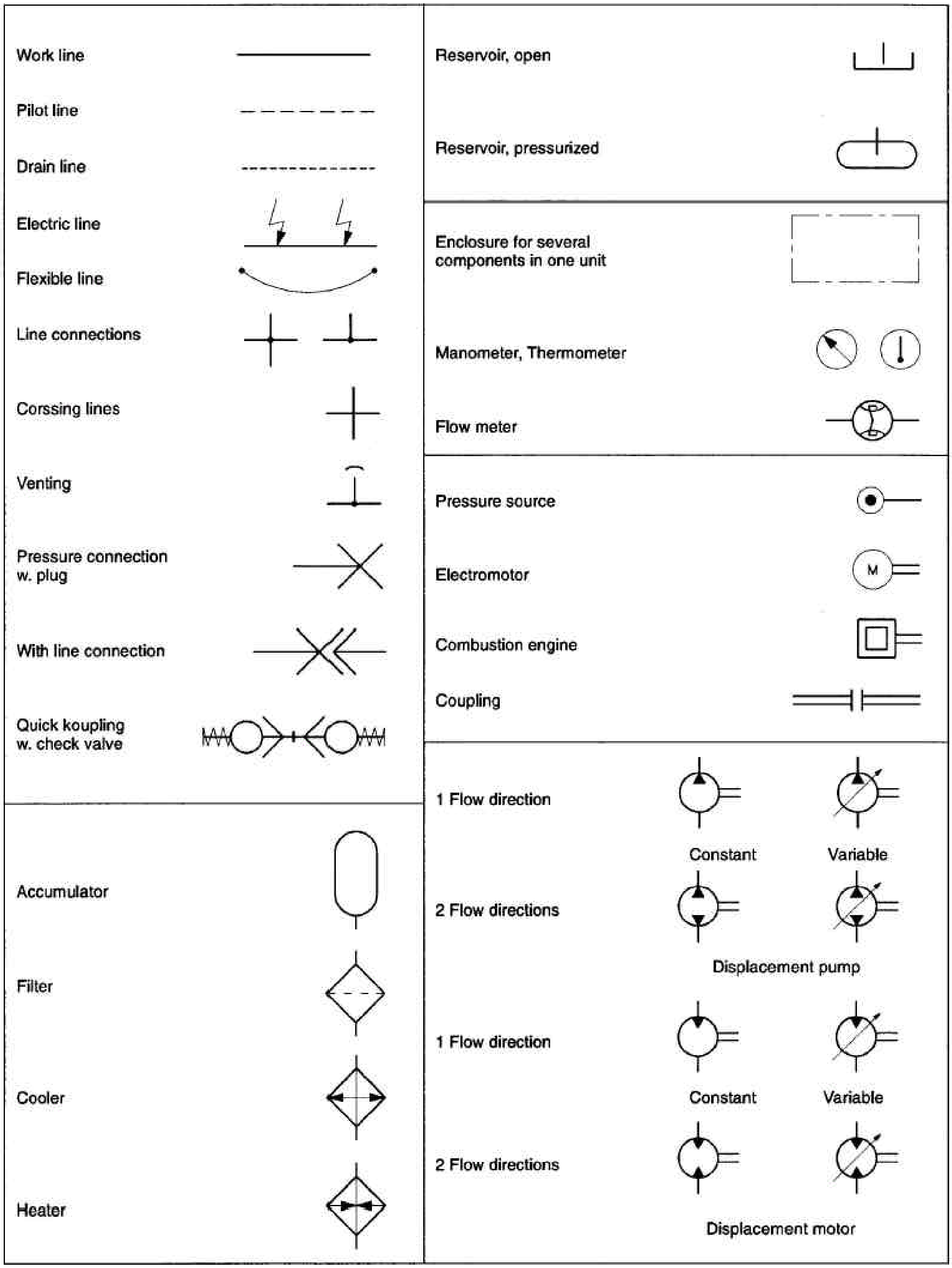
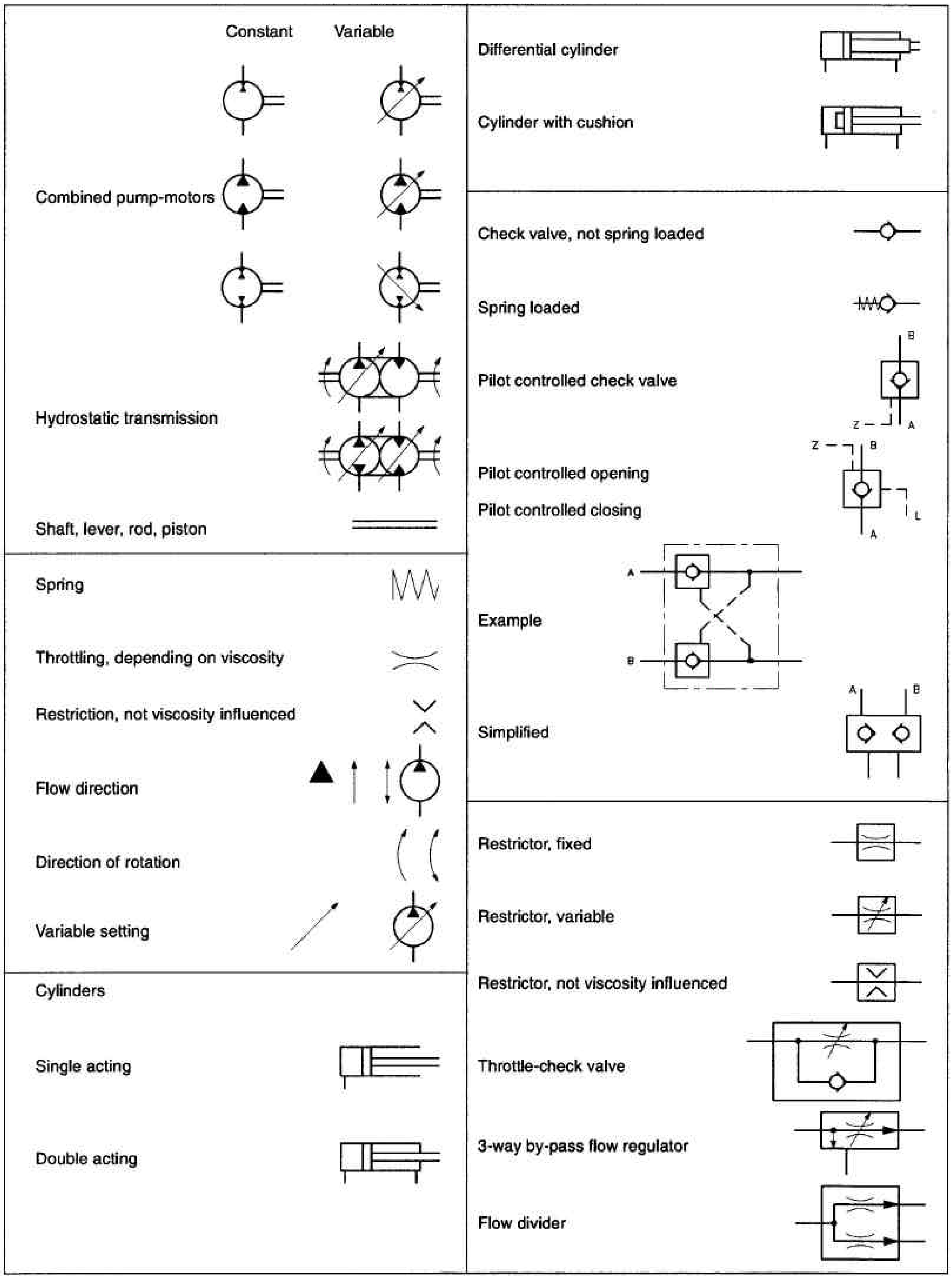
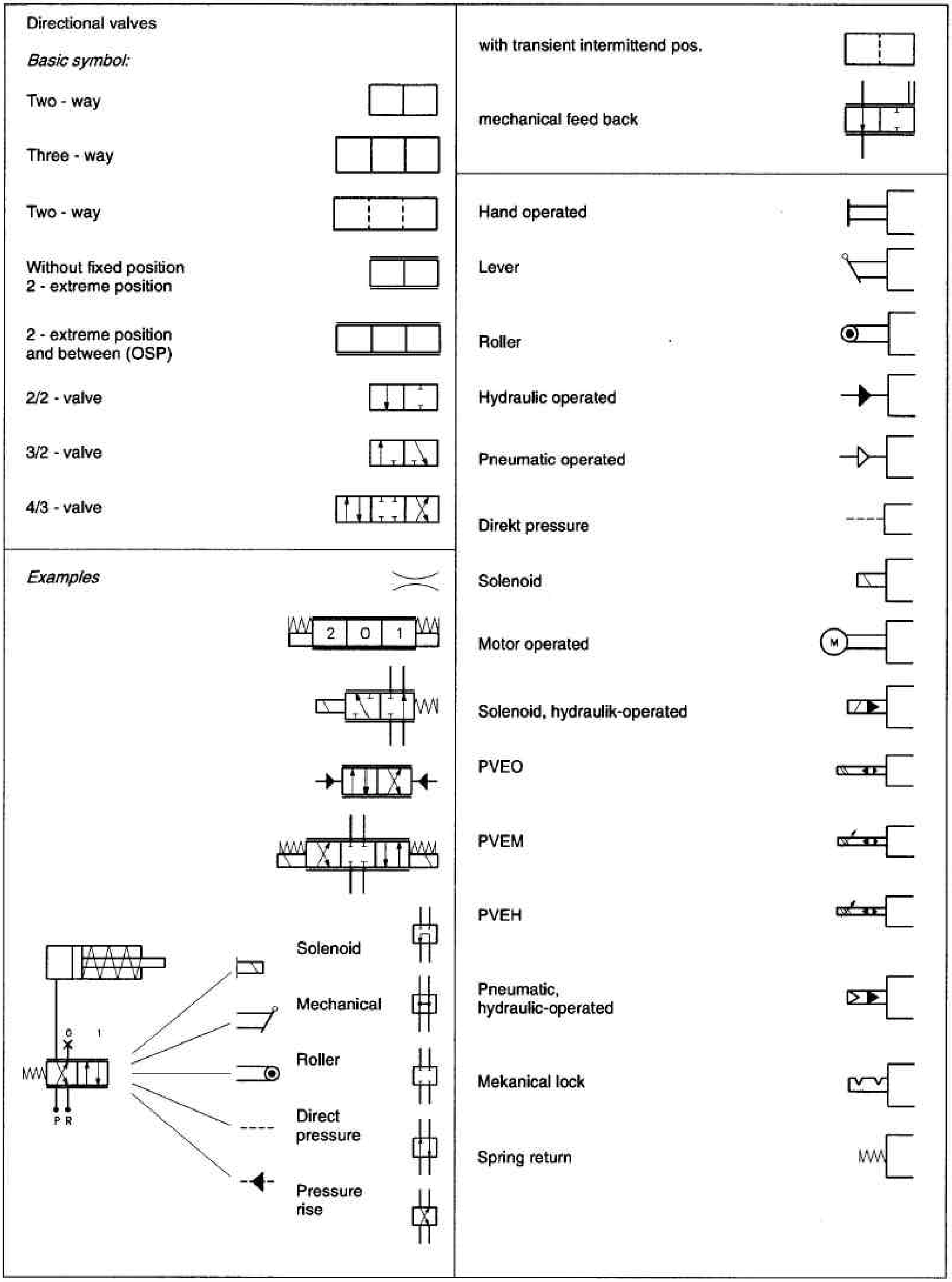
Appendix A – Hydraulic Symbols

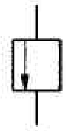
The symbols were provided by www.HydraulicSupermarket.com



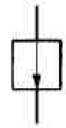

Constant
Variable
Combined pump-motors
Hydrostatic transmission
Shaft, lever, rod, piston
Spring
Throttling, depending on viscosity
Restriction, not viscosity influenced
Flow direction
Direction of rotation
Variable setting
Cylinders
Single acting
Double acting
Differential cylinder
Cylinder with cushion
Check valve, not spring loaded
Spring loaded
Pilot controlled check valve
B
Z
A
Pilot controlled opening
Pilot controlled closing
L
Example
Simplified
Restrictor, fixed
Restrictor, variable
Restrictor, not viscosity influenced
Throttle-check valve
3-way by-pass flow regulator
Flow divider


Directional valves
Basic symbol:
Two - way
Three - way
Two - way
Without fixed position
2 - extreme position
2 - extreme position
and between (OSP)
2/2 - valve
3/2 - valve
4/3 - valve
Examples
2
0
1
0
1
P R
Solenoid
Mechanical
Roller
Direct
pressure
Pressure
rise
with transient intermittend pos.
mechanical feed back
Hand operated
Lever
Roller
Hydraulic operated
Pneumatic operated
Direkt pressure
Solenoid
Motor operated
M
Solenoid, hydraulik-operated
PVEO
PVEM
PVEH
Pneumatic,
hydraulic-operated
Mekanical lock
Spring return

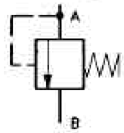
Normally closed



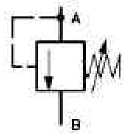
Normally open



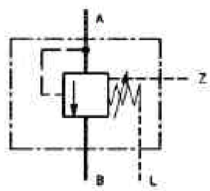
Pressure limiting valve, fixed setting



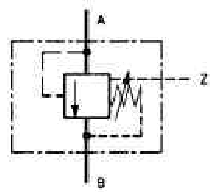
Pressure limiting valve, variable



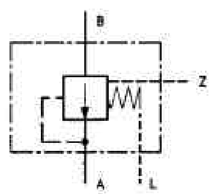
Pilot operated, external drain line



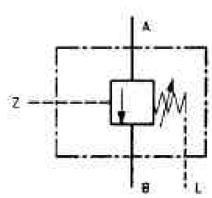
Internal drain



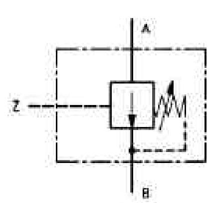
Pressure reduction line



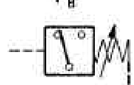
Pilot controlled opening valve



Pilot controlled closing valve



Pressure switch



A.B. Work lines

P. Pump connection (pressure)

R.S.T. Return /Tank

X.Y .Z. Pilot line

L, Drain line

Vita

Christopher Rome Terwelp was born August 10, 1979 in Austin, TX. He is the son of Dan and Diane Terwelp. After graduating from Westlake High School in Austin, Chris pursued a degree in engineering at Virginia Polytechnic Institute and State University in the fall of 1997. He graduated with a Bachelor of Science in Mechanical Engineering in December of 2001, and then Chris continued his studies at Virginia Tech at the graduate level. Chris received a Master of Science degree in Mechanical Engineering from Virginia Tech in May of 2003.