

University of Nevada, Reno

**HARDWARE MODIFICATIONS FOR ELECTRO-HYDRAULIC
CONVERSION AND IMPLEMENTATION OF COMPUTER-
ASSISTED CONTROL ON A LARGE MINING SHOVEL**

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN
ELECTRICAL ENGINEERING

BY

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THE GRADUATE SCHOOL

We recommend that the thesis
prepared under our supervision by

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entitled

**Hardware Modifications For Electro-Hydraulic Conversion And Implementation
Of Computer-Assisted Control On A Large Mining Shovel**

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requirements for the degree of

MASTER OF SCIENCE

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Abstract

Computer-assisted control with human supervision plays a key role in efficient control of surface mining equipment such as excavators. A control architecture that incorporates human control input and sensory feedback has been developed for application in multilink electro-hydraulic machines in mining industry. This system was successfully tested and demonstrated on a small-scale excavator at the University of Nevada, Reno (UNR). The aim of this thesis is to investigate the feasibility of implementing this computer-assisted control technology on large mining shovels used in surface mining. In order to implement this control system on Hitachi EX3500 excavator, several hardware modifications are proposed. The major modification is conversion of hydraulically operated machine into electro-hydraulic control. A Programmable Logic Controller (PLC) has been used to interface the new electro-hydraulic system with the control computer that implements the computer-assisted control. The hardware was tested on a test bench in a laboratory setting and the electro-hydraulic valve control was demonstrated. The test results show that the control technology can be implemented on the large mining shovels to provide efficient and coordinated control of the machine.

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1. Introduction

1.1. Motivation

The operation of a mining machine with multiple and articulated joints requires a skilled human operator to coordinate the movement of the machine links. The efficient use of surface mining equipment such as excavators, loading and hauling machines depends on the skill and experience of the operator to control the machine and move the tool along a desired path. The aim of an excavator operator is to perform a loading task easily with optimum bucket fill and minimum strain on the machine equipment. This task demands continuous concentration of the operator to control the multiple links simultaneously. In order to improve the efficiency of these types of machines and to reduce the operator fatigue, there exists a demand for a system that would make the machine operation easy and more intuitive for unskilled operators. Using such a system in the mining machines would greatly improve the productivity by reducing the time to fill the bucket. This demand can be accomplished by employing a robot-human operated system which incorporates human control input and sensory input to provide efficient and coordinated movement of the machine.

Robotics used in manufacturing industry cannot be aptly used to automate the mining machinery operations since the working environment in the mines changes continuously and the tasks are not repeated precisely. Mine machines such as large front shovels has to perform several hundred loading cycles per day. In each loading

cycle the operator should carefully move the bucket along a desired trajectory and fill the bucket with maximum load. To achieve this coordinated motion the operator has to control three or more control inputs which make the task extremely difficult to master. Roberts and Croke (1997) described automated load-dump haulage road headers and Stenz, et al. (1999) proposed using sensory adjustments to vary the digging and loading points in the operation of a front shovel. Human supervisory control is necessary while integrating of such fully robotic operated system in to the complex mining and construction equipment.

A computer-assisted system with human supervisory control will effectively improve the efficiency of the machine. Computer-assisted human control architecture is accomplished with an onboard computer in the machine. This computer (called as control computer from now on) accepts input signals (Joystick signals) from the human operator along with signals from position sensors that are attached to the machine joints. The control computer calculates a set of coordinated machine control signals using the input joystick signals and feedback position signals.

With computer-assisted human control installed in a mine machine, it can be operated in two different modes – 1. Manual mode and 2. Computer-assistance mode. Under normal manual mode, the machine is completely operated by the human operator and the computer plays no role in the machine control. The operator provides the input via joysticks and other control devices. These input signals are directly passed to the electro-hydraulic valves controlling the machine actuators. In this mode, the

operator has to simultaneously control each joystick to achieve a coordinated motion of the machine making the task difficult.

In computer-assistance mode, the input signals from the human operator are first send to the control computer which generates the required valve signals to control the machine actuators. In this mode the operator input need not to be signals from each joystick but can be a simplified bucket trajectory selection signal. The control computer accepts the input in this simplified form along with the position feedback signals from sensors and generates the coordinated control signals for each actuator according the bucket trajectory selected by the operator. With control computer generating the coordinated motion, simultaneous control of joysticks is not necessary in this mode and that makes the operation of the machine much easier even for an unskilled operator. The concept of computer-assisted human control is illustrated in Figure 1.

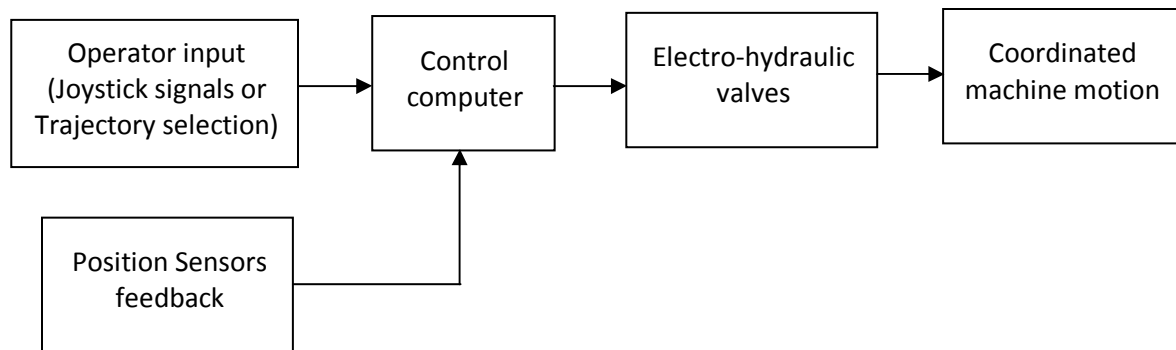


Figure 1: Illustration of computer-assisted human control concept.

Danko, Knowles and Tiwari (2005) & (2006), Danko (2007) proposed a robot-human control architecture that is developed at the University of Nevada, Reno (UNR). This

control system has been extensively tested in simulation and also on a small-scale prototype Bobcat 435 mini-excavator in a laboratory setting at UNR. With the successful results of these tests it is believed that the similar system can be used in the large-scale mine machines such as mine shovels.

1.2. Research Objectives

The primary objective of this research is to test and demonstrate the feasibility of implementing the previously developed computer-assisted control architecture on a large surface mining shovel. A system has been developed to test the proposed control architecture on a Hitachi EX3500 mining shovel which is commonly used in modern surface mining industry. In order to install this system on the shovel it needs to be converted in to electro-hydraulic control which currently has hydraulic control. This conversion requires several hardware modifications in the shovel.

The hardware modifications required for the conversion of hydraulic control of the machine to electro-hydraulic control has been designed. The selected hardware was tested on a test bench in a laboratory setting with working environment similar to Hitachi EX3500 to ensure the operation of shovel will not be altered when the control architecture is installed on it. All the selected components are interconnected through a central communication controller which performs data acquisition and valve control for the system.

A commercially available Programmable Logic Controller (PLC) was selected to act as communication controller. This PLC was programmed to operate the control system in manual and computer-assisted modes. The electro-hydraulic valve bank control using electronic joysticks was tested and demonstrated on the test bench. These tests show that with the hardware modifications, the control system can be implemented on the large shovel.

The work presented in this thesis is a part of the research work done by the robotics laboratory research team at University of Nevada, Reno. The team includes Mr. Jeremy S. Knowles, Mr. Satayjith Bobba and Mr. Jacob Carr.

1.3. Organization of Thesis

A brief description of each chapter in this thesis is given here.

Chapter 2: Background Review

This chapter provides a literature review of robotics use in mining industry and applicability of computer-assisted control in large-scale mine machines such as shovels and excavators.

Chapter 3: Computer-Assisted Control Architecture

This chapter describes the concept of computer-assisted control architecture previously developed at UNR. This control system is tested in simulation and using a small-scale prototype excavator. The results of these tests are presented in this section.

Chapter 4: Hard Modifications for Hitachi EX3500 Shovel

This chapter discusses the required hardware modifications on Hitachi EX3500 in order to implement the proposed computer-assisted control system. The major hardware modification needed is the conversion of the hydraulic control of the machine to electro-hydraulic control. The conversion requires replacement of mechanical pilot joysticks currently on the shovel with electronic joysticks and hydraulic control valves with electro-hydraulic proportional valves and installation of relative position sensors

Chapter 5: Test Bench Assembly and Programming

This chapter discusses the assembling of the selected hardware on a test bench for testing before installing on the shovel. This is required to make sure the normal operation of the machine is not hampered by the use of new hardware. Also included in this chapter is the programming of the PLC to communicate with the hardware and control computer software to implement the control architecture.

Chapter 6: Results and Discussions

In this chapter, the test bench results are presented and implementation of the computer-assisted control system on the Hitachi EX3500 shovel is discussed.

Chapter 7: Conclusions and Future Work

In this chapter, the benefits of the proposed system in the mining industry are presented along with recommendations for future work.

2. Background Review

In this chapter a brief review of relevant literature in the field of automation and robotic control in mining industry is given. This includes work on machine kinematics, machine modeling, development of electro-hydraulic controller for mining equipment, implementation robotic control for machine automation and development of computer-assisted control for mine shovels and excavators.

2.1. Machine Dynamics and Kinematics

Mining machines are generally characterized by multiple and articulated joints. In order to automate such machines knowledge of the kinematics and dynamics of the machine is required. A systematic procedure to describe the kinematics relationships of excavators is proposed by Koivo (1994). The relationship between the position and orientation of the bucket, the machine joint angles and the cylinder lengths are described. Forward and inverse kinematic relations are also described to develop the corresponding velocity relations for the excavators.

A dynamic model for an excavator is developed by Koivo et al. (1996) by applying Newton-Euler equations to each link of the machine in succession. Based on the model, a proportional differential controller for an excavator was designed to track a specified bucket trajectory. Frimpong et al. (2008) proposed dynamic models of an hydraulic excavator using Newton-Euler techniques. The model describes the dynamics of the machine links, boom, arm and bucket.

Hemami (1994) presented the relationship between the resistive forces acting on the bucket and energy consumption of the machine. An approach to determine a bucket trajectory with minimum energy consumption is described. The concept is used to automate the scooping and loading operations of a Load-Haul-Dump (LHD) loader.

Singh (1995) proposed a model to predict the resistive forces acting on the bucket during excavation. In this method, previous experimental data is used for learning and predicting the future resistive forces. A set of linear equations were developed to determine the unknown resistive forces. The learning methods described include global regression; memory based learning and neural net techniques.

Tafazoli et al. (1999) proposed a method for experimentally determining the link parameters such as torque, friction and inertia. This method was tested on a instrumented Takeuchi TB035 mini excavator. Position sensors are used to measure the machine joint angles and pressure transducers are installed on the links to measure the forces exerted by the cylinders. A set of differential equations were developed to indirectly measure the inertial parameters using the recorded sensor data.

2.2. Controllers for Mining Equipment

A significant amount of work has been done in the field of controller design to assist the shovel operators to accurately position the bucket during excavation. An sliding mode controller to implement impedance control for a backhoe excavator was developed by Ha et al. (2000). The dynamic relationship between the bucket tip position

and bucket-soil interaction forces is described. The sliding mode controller incorporating a fuzzy tuning approach is used to control position of the cylinders in hydraulic actuators. The control system was tested in simulation and using a prototype excavator.

A relatively simple control system without using any sensors or transducers mounted the machine is proposed by Budney et al. (2003). The relationship between the bucket velocity and the oil flow into the cylinders is described. A micro computer calculates the oil flow signals and generates the corresponding valve actuating signals. The load-independent valves are able to position the hydraulic cylinders without any sensor feedback.

Conventional control systems so far discussed are successfully implemented in either simulation or tested on mini excavators. Implementing such systems on large-scale shovels is a difficult task because the nonlinearities in the hydraulic actuators and the resistive forces on the machine increase with the size of the machine. Lee and Chang (2002) proposed a linear dynamic model for an excavator and developed a controller based on time-delay control using switching action. The controller uses the error measurements of previous time steps to determine the dynamics of the system. This control system is tested using a 21-ton Hyundai HX60W-2 excavator with a speed level at which a skillful operator work.

Nyugen et al (2000) and Nyugen (2000) presented a dynamic model of a electro-hydraulic system based on the forces acting on the cylinders. With this dynamic model a

controller was designed for electro-hydraulic actuator. A relation between the position of the machine and forces acting on the cylinders is described. The control input for the system is the force resulting from the desired machine dynamics. This control system tested with a prototype excavator to track a desired trajectory.

A path tracking control system for a large hydraulic excavator was proposed by Chiang and Huang (2004). Model Reference Adaptive Control (MARC), that uses an on-line self tuning algorithm for position error correction is described. A third order dynamic model of the hydraulic excavator is used to develop the tracking controller. Electronic Pressure Control (EPC) valves are installed on the excavator along with a PID valve controller to drive the cylinders. The control system is tested using the modified excavator to track a horizontal straight line path and a control accuracy of ± 2 cm is achieved.

Gu et al. (2004) proposed a Proportional-Integral-Plus (PIP) controller for the Lancaster University Computerized Intelligent Excavator (LUICE). A bucket position controller to improve the joint control and provide accurate movement of the excavator arm was described. A non-linear dynamic machine model for LUICE was developed to test the control algorithms in simulation. The PIP controller performance to maintain the desired trajectory was analyzed in MATLAB/SIMULINK.

A real-time dynamic machine model identification method was described by Danko (2007) for computer-assisted control of multiple-link hydraulic excavator. The

model uses Kinematics differential equations of each machine link. The dynamic model is used in the closed loop control of each of the machine link. The model parameters representing link masses, inertia, hydraulic actuator coupling and external forces are identified and updated dynamically in real-time during machine motion. This control system was tested using a prototype Bobcat 435 mini excavator. This controller is used in the computer-assisted control architecture for large-scale mine shovels presented in this thesis.

3. Computer-Assisted Control Architecture

3.1. Overview

To introduce computer assistance to human operator in the operation of mine machine, a control system was proposed by Danko (2007), Danko, Knowles and Tiwari (2005) & (2006). This control system is developed and tested in a laboratory setting at UNR. The aim of this system is to transform the normal, manual control of the machine to computer-assisted control. In manual control, the operator directly controls the machine by controlling the motion of each hydraulic cylinder through a single joystick input. In order to move the bucket along a desired trajectory, the motion of the three or more links must be coordinated by the operator continuously which is a difficult task to master. Manual control of hydraulic actuated machine is illustrated in Figure 2.

Under computer-assisted control, the operator input joystick signals are sent to a control computer instead of control valves. The control computer is also supplied with the feedback signals from the position sensors installed on the each joint of the machine. The computer then calculates coordinated output valve control signals required to move the machine according to a kinematics transformation selected by the operator. Computer-assisted control scheme for an electro-hydraulic machine is illustrated in Figure 3.

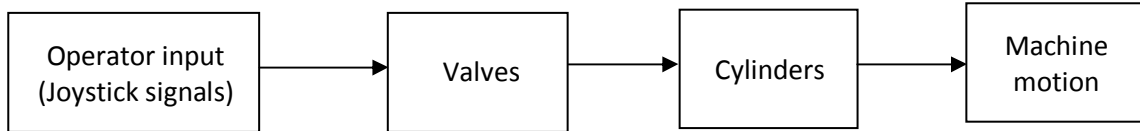


Figure 2: Schematic diagram of manual control for hydraulic machine

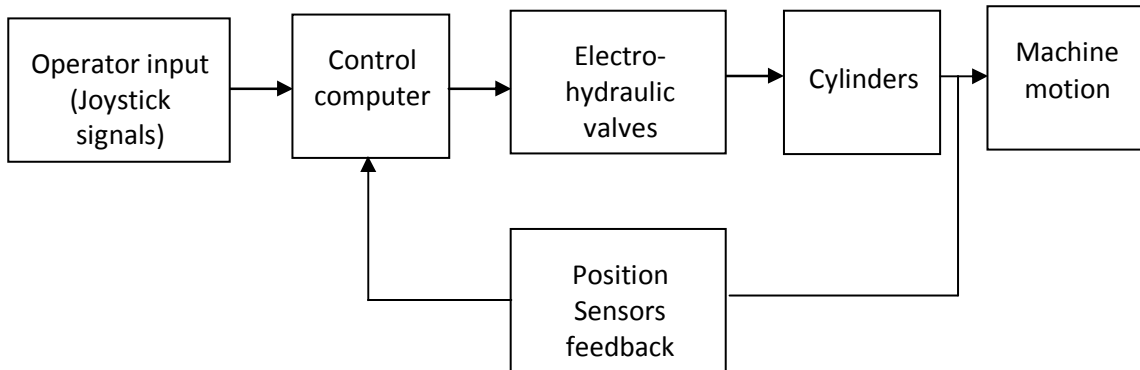


Figure 3: Schematic diagram of computer-assisted control for electro-hydraulic machine

3.2. Control Architecture

In computer-assisted control, the input joystick control signals are used to control a virtual machine with a transformed kinematics different to real machine. The control computer determines a desired trajectory according to the input signals supplied to the virtual machine. The inverse of this kinematics selection is then performed to calculate the coordinated control signals for the real machine. These control signals will be sent to valves to accomplish the desired bucket trajectory. The control computer also generates a closed-loop error correction using the position sensor feedback signals based on a model identification and control system developed by Danko (2007). The signal flow diagram of this control architecture is illustrated in Figure 4.

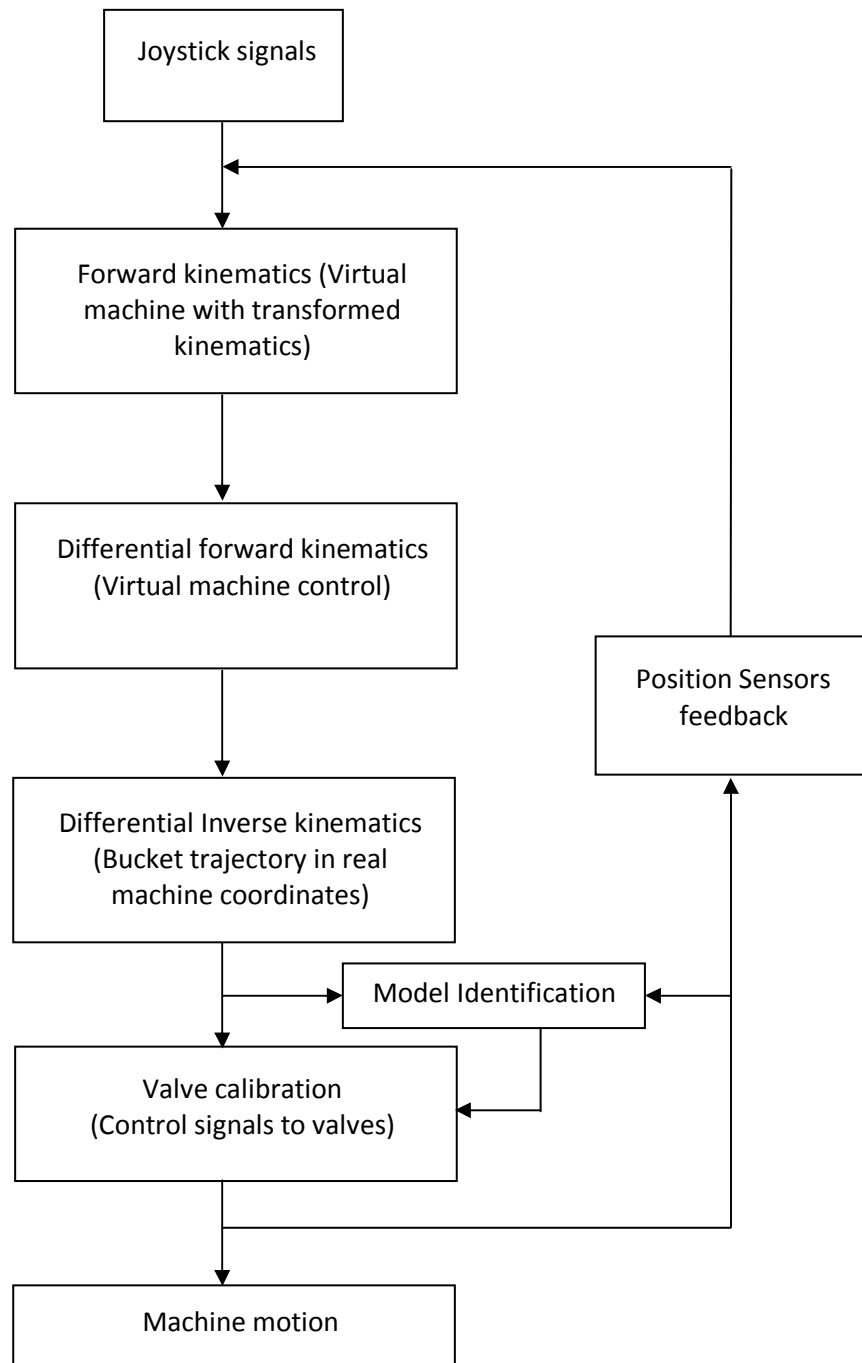


Figure 4: Signal flow diagram of computer-assisted control architecture

3.2.1. Forward Kinematics

Forward kinematics is the transformation real machine kinematics in to virtual machine kinematics. The real machine kinematics of a three link excavator is illustrated in Figure 5. L_1 , L_2 and L_3 are the lengths of the machine links boom arm and bucket respectively. Cartesian coordinates is an example of kinematics transformation demonstrated using the prototype excavator at UNR. With three independent joystick input signals, the operator controls the virtual machine that moves in Cartesian coordinates. The relative angles between the machine links are determined using the position sensor readings. The three angles θ_1 , θ_2 , and θ_3 are the boom, arm and bucket link angles respectively as shown in Figure 6. The forward kinematics functions uses these angles and precisely measured lengths of the machine links to calculate the Cartesian coordinates of the bucket edge position (X,Y,Z).

$$(X, Y, Z) = f(\theta_1, \theta_2, \theta_3)$$

Where $\theta_1, \theta_2, \theta_3$: Boom, arm and bucket link angles

X, Y, Z: Cartesian coordinates of the bucket edge position.

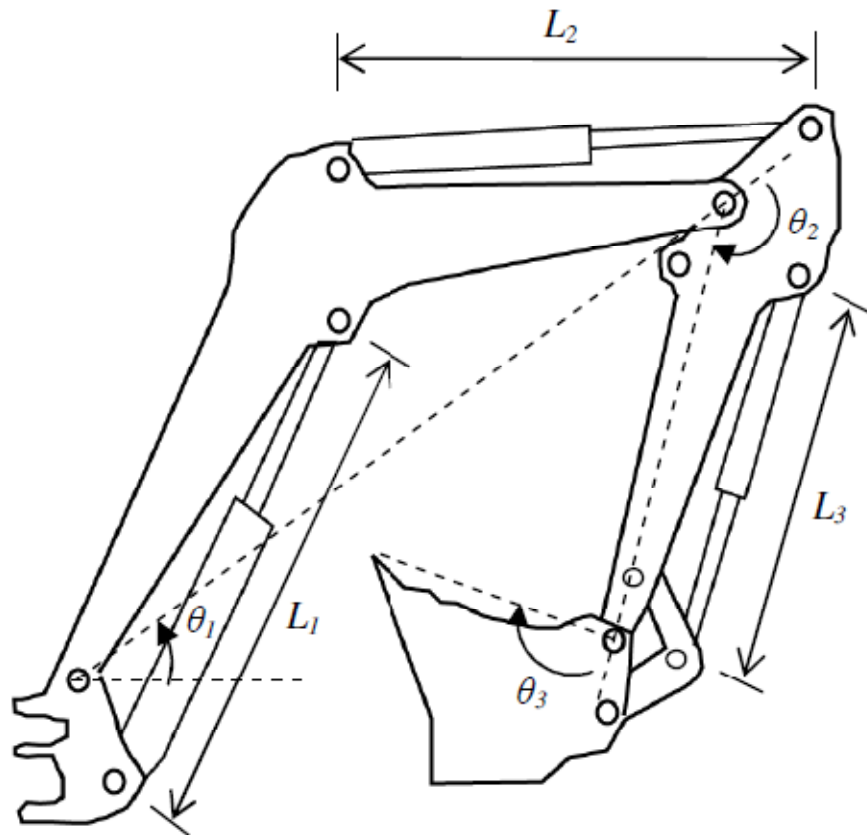


Figure 5: Real machine kinematics of a 3-link excavator

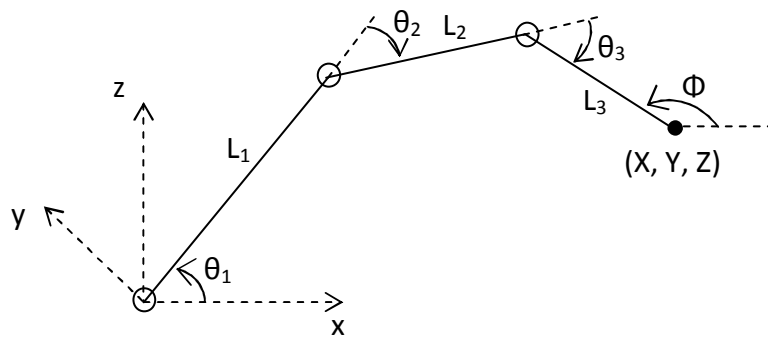


Figure 6: Virtual machine kinematics

3.2.2. Differential Forward Kinematics

Differential forward kinematics function generates differential movement of the bucket edge position in the virtual machine coordinates using the input joystick signals and the virtual coordinates from forward kinematics. Figure 7 shows the differential movement of the bucket edge position with a slope angle of α . These differential movements are used to calculate the final position of the bucket edge in virtual machine coordinates.

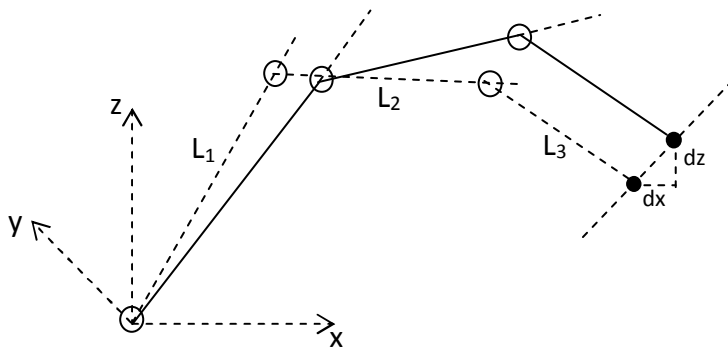


Figure 7: Differential movement of virtual machine Cartesian coordinates

$$(dX, dY, dZ) = f(J_{bm}, J_{am}, J_{bk}, X, Y, Z)$$

Where, dX , dY , dZ : Differential movements of the bucket edge along X, Y and Z directions respectively

J_{bm} , J_{am} , J_{bk} : Input joystick control signals for boom, arm and bucket respectively

X , Y , Z : Cartesian position coordinates of the bucket edge position.

3.2.3. Differential Inverse Kinematics

The differential inverse kinematics function uses an inverse kinematics transformation to calculate the initial and final position of the bucket edge in the real machine coordinates from the final position calculated in virtual machine coordinate system. From these initial and final position coordinates of real machine, the desired bucket trajectory is determined. This desired trajectory is a time-series of bucket positions and orientations. For each time step the angular displacements of each machine link are calculated.

$$(d\theta_1, d\theta_2, d\theta_3) = f(dX, dY, dZ, X, Y, Z)$$

where, $d\theta_1, d\theta_2, d\theta_3$: Relative angular displacements of boom, arm and bucket respectively

dX, dY, dZ : Differential movements of the bucket edge along X, Y and Z directions respectively

X, Y, Z : Cartesian position coordinates of the bucket edge position.

3.2.4. Error Signal Generation

The differential link angles determined in the previous section are used as reference angles in the feedback loop to calculate the position error of the bucket. The actual machine link angles calculated from the position sensor feedback are compared with the reference angles. Bases on the error between the actual angles and reference angles, a differential error correction signal will be generated using the dynamic model

identification for differential machine control developed by Danko (2007). The error correction signal is passed to the valve calibration function to correct the position error.

3.2.5. Valve Calibration

The control computer uses the angular displacements obtained from the differential inverse kinematics function to calculate the valve control voltages required to accomplish the desired trajectory. The position error correction signal from the model identification function is also used in calculating the valve voltages.

The implementation of this Cartesian kinematics control has been tested in both simulation and experiment by Danko et al. (Danko, Knowles and Tiwari, 2005), (Danko, Knowles and Tiwari, 2006). Cartesian kinematics virtual machine is one of the simple kinematics transformation implemented using the computer-assisted control system. Any virtual machine kinematics that uniquely defines the position and orientation of the bucket can be used with this system.

3.3. Testing of Computer-Assisted Control on Prototype Excavator

The control architecture discussed so far in this section has been demonstrated by Danko et al. using a Bobcat 435 excavator. The hardware modifications made to this excavator to test the control system are presented here. Understanding of these modifications is required because in section 4 and 5 similar hardware modifications for a large mining shovel are discussed. Figure 8 shows the Bobcat 435 mini excavator used for testing the control system. The hydraulic valve bank on the machine is replaced with

electro-hydraulic valve bank shown in Figure 9. Figure 10 shows the joysticks in the machine cab. With these modifications the excavator is converted to electro-hydraulic control from hydraulic control. The position sensors installed on the boom, arm and bucket cylinders are shown in Figure 11. These position sensors measure the linear position of the each of the cylinder. This position data is then used to find the angular position of the each machine link. Figure 12 shows the control computer installed in the cab of the machine.

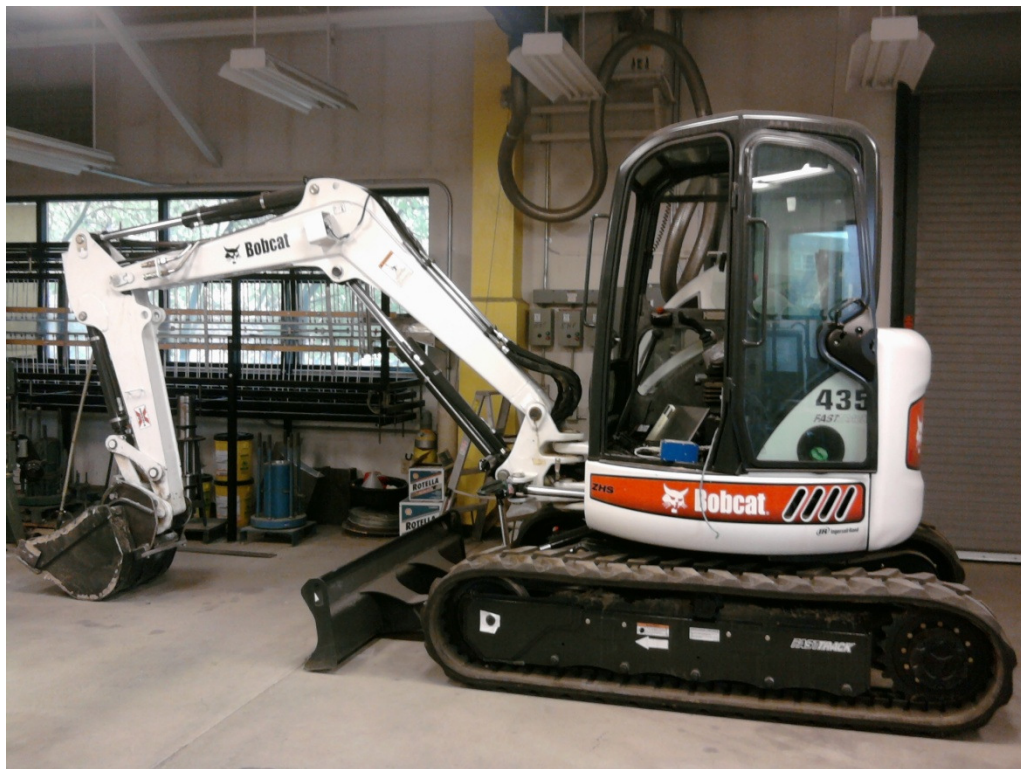


Figure 8: Bobcat 435 experimental excavator



Figure 9: Electro-hydraulic valves installed on Bobcat 435 excavator



Figure 10: Electronic joysticks

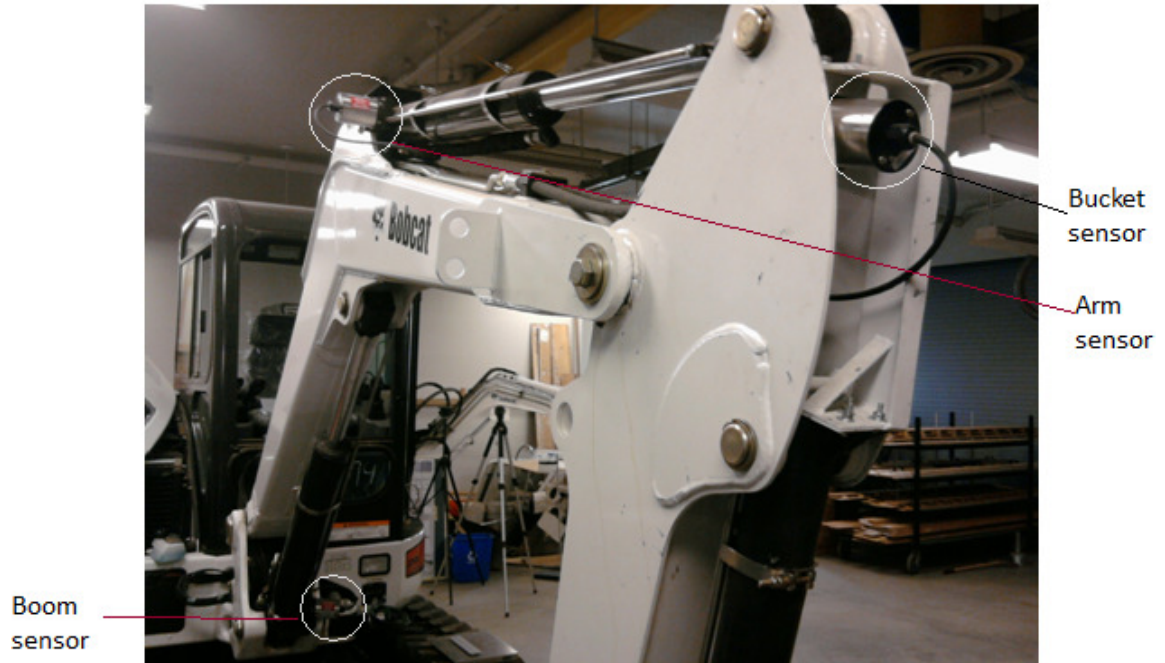


Figure 11: Position sensors installed on boom, arm and bucket cylinders



Figure 12: Control computer installed in the cab of Bobcat 435 excavator.

Examples of the simulation and experiment results are shown in Figure 13 and 14. Figure 13 shows the simulation results of computer-assisted control of bucket pin joint and bucket edge along a square trajectory. The green square in the figure is the bucket pin joint and the red square is the bucket edge. Figure 14 shows the experiment results in which the excavator is operated under computer-assisted control using a Cartesian virtual machine kinematics with a slope angle of 45° . In this test the joint between the arm and the bucket was controlled along a 45° square trajectory. The test results show that the closed-loop error correction system in the computer-assisted control works well to accomplish the desired trajectory.

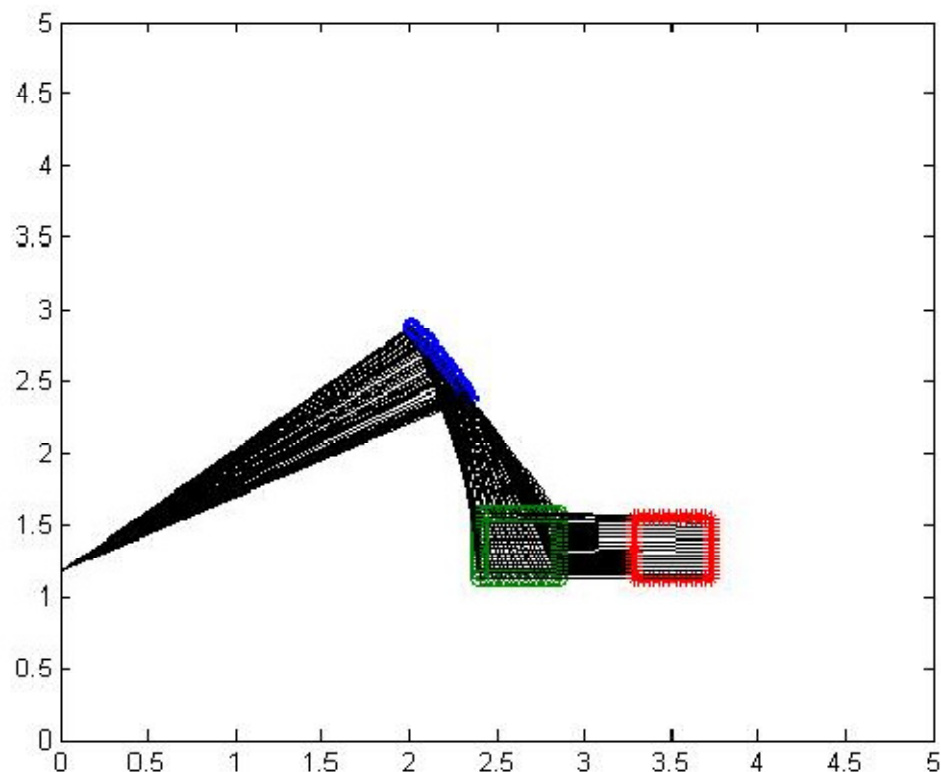


Figure 13: Simulation results of Computer-assisted control system



Figure 14: Testing of Computer-assisted control system using Bobcat 435 excavator

4. Hard Modifications for Hitachi EX3500 Shovel

4.1. Overview

The aim of this research is to test the feasibility of implementation of computer-assisted control system discussed in chapter 3 on Hitachi EX3500 mine shovel. In order to install the new control system on the Hitachi shovel, several hardware modifications are needed. These modifications have been designed and the hardware has been selected, acquired and assembled on a laboratory test bench for testing at UNR. The hardware components to be added are shown schematically in Figure 15. This design was developed working along with Carr (2008). The major hardware modification needed is the conversion of the direct hydraulic pilot control of the machine to electro-hydraulic control. This is necessary to allow control signals from electronic joysticks to be sent to the central motion control computer. The central motion control computer must then be able to control the machine's hydraulics in robotic assistance mode through electronic signals.

The hardware additions consist of electronic joysticks, electro hydraulic pressure reducing valves which will send appropriate control pressures to the pilot operated main valve banks of the shovel, rotary encoders which will be used to measure the relative angular positions of each of the three machine joints, an orientation sensor that will be installed in the cab of the machine and will measure the orientation of the machine base, and a control computer that will run the computer-assisted control software.

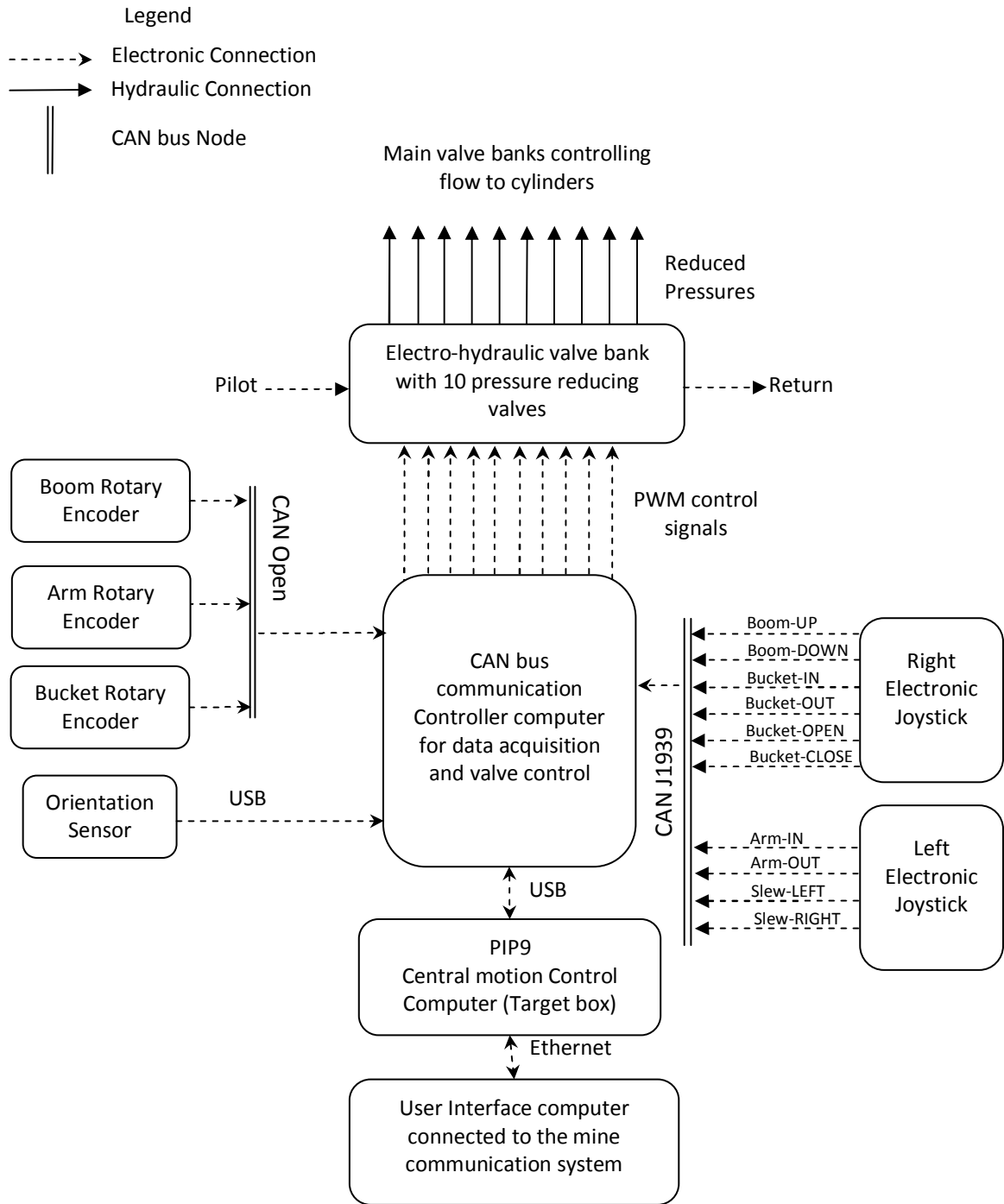


Figure 15: Schematic diagram of hardware modifications planned for Hitachi EX3500 shovel

The selected hardware components are interconnected through a communication controller to perform the required data acquisition and valve control operations. A commercially available programmable logic controller (PLC) is selected as a communication controller.

The input signals from the joysticks and the sensor readings are fed to the main communication controller using CAN bus protocol. The controller will send this data to the central motion control computer to execute robot assistance to the operator. It will be possible to work without the use of the central motion control computer, if a completely manual, ordinary shovel operation is chosen. If, however, a robotics-assisted operation is desired, the central motion computer must be also be turned on, in order to activate the motion control software to calculate the output signals to be sent to the pilot valves. The communication controller will receive these valve output signals from the central motion control computer and converts them to pulse width modulated (PWM) signals to be sent to the pilot valve bank, controlling the pressure output.

4.2. Electronic Joysticks

The hardware design uses electronic joysticks which will replace the mechanical pilot joysticks currently in the shovel. The joysticks selected are *JC6000* multi axis joysticks, shown in Figure 16, commercially available from *Penny Giles control Company*. These joysticks are supplied with an integrated CAN bus output using J1939 protocol. With the CAN bus output the Joysticks can be directly connected to the communication controller. 6 pin Deutsch connectors are used for the electrical connections.

The movement of joystick in each direction provides an 8-bit digital signal to the communication controller. The two joysticks are configured to generate 10 control signals as shown in Figure 15. The bucket open and close signals will be controlled by a rocker switch on the right joystick. Alternatively, these two signals could remain unmodified and could be controlled by the mechanical pilot control foot pedal currently installed on the shovel.



Figure 16: JC6000 electronic joysticks

4.3. Communication Controller

The communication controller used in the hardware design performs data acquisition and valve control for the system. The controller accepts input signals from joysticks and sensors. These signals are then sent to the control computer which executes the computer-assisted control software and generates the valve control

signals. The communication controller converts these output control signals in to PWM signals which are sent to the valve bank controlling output pressure. The communication controller selected for this is a *DIGSY Compact* controller, commercially available from InterControl. The *DIGSY Compact* controller, shown in Figure 17 is a programmable logic controller specifically developed to work on mobile or stationary equipment in harsh environmental conditions. The controller handles a maximum of 24 digital (CAN bus, USB, or serial) inputs, 8 analog inputs and 16 digital or PWM outputs.



Figure 17: *DIGSY Compact* communication controller

The communication controller was programmed to convert the raw sensor and joystick signals to numerical values that can be used by the control software, and to convert the numerical output signals from the control computer to PWM signals that can be sent to the valves. PROSYD1131, specially designed PLC programming software is used for programming the *DIGSY Compact* controller.

4.4. Control Computer

The control computer executes the previously developed computer-assisted control software discussed in chapter 3. A *PIP9* industrial PC will act as the control computer for this system. This computer is shown in Figure 18. The control computer is also connected to a user interface computer. This user interface computer will be used to monitor the software control and to send the bucket position data to mine communication system which is used for ore grade control.



Figure 18: PIP9 control computer

4.5. Rotary Encoders

The sensors selected for the hardware design include three rotary encoders. These encoders are relative rotation sensors to provide the relative angular position of each of the three machine links. These sensor signals are used by the control computer to calculate the position of the bucket. This data could be used by mine

operators along with GPS data for the position of the base of the machine to determine the position and orientation of the bucket in absolute coordinates. This is useful for ore grade control analysis. The sensors selected for this are EXGA rotary encoder. These are explosion proof, single turn rotary encoders specially designed for installation in heavy-duty industrial applications. The encoders consists of inbuilt CAN interface that works using CAN open protocol. Figure 19 shows the selected EXGA rotary encoder and Figure 20 shows the connection cap drawing and CAN bus configuration settings of the encoder from specification sheet.



Figure 19: EXGA rotary encoder

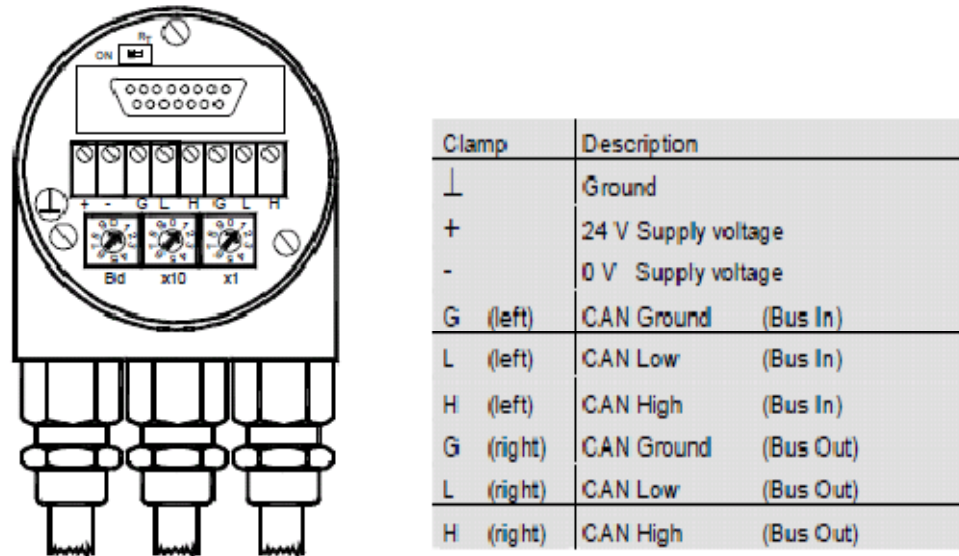


Figure 20: Connection cap diagram and CAN bus configuration of EXGA rotary encoder

The encoders should be installed on the pin joints of the each of the machine links, boom, arm and bucket. All the three encoders are connected to the communication computer through CAN bus using CAN OPEN protocol. The control computer receives the angular position data and sends it to the control computer.

4.6. Absolute orientation sensor

In addition to the rotary encoders, an absolute orientation sensor is planned to install in the cab of the Hitachi EX3500 shovel. This sensor provides 3-dimensional data on the orientation of the base of the machine in the form of azimuth pitch and roll angles. A commercially available 3DM-GX2 sensor from Microstrain, shown in Figure 21 is used for this purpose. The sensor is incorporated with a triaxial accelerometer, a triaxial gyro, a triaxial magnetometer, and a processor to determine the three-dimensional orientation of the sensor. The sensor operates at a speed of 100 Hz.



Figure 21: 3DM-GX2 absolute orientation sensor

Laboratory evaluation of this sensor was conducted in order to determine if it would provide acceptably reliable and accurate readings when installed on the shovel. The sensor was determined to be acceptable for this purpose (Carr, 2008).

4.7. Electro-Hydraulic Valve Bank

As discussed in section 4.1, conversion of Hitachi shovel to electro-hydraulic control is required to install the computer-assisted control technology. The conversion requires installation electro-hydraulic proportional pressure reducing valves in the place of hydraulic pilot valves currently in the shovel. An electro-hydraulic valve bank with 10 valves supplied by Sauer-Danfoss is used for this purpose. The valve bank with attached pressure gauges is shown in Figure 22. These valves are operated by pulse width modulated (PWM) signals. All the valves are connected to the communication controller

using *Deustch* connectors. The communication controller converts the valve control signals from control computer in to PWM signals and sends to the electro-hydraulic valve bank to control the output pressure.



Figure 22: Electro-hydraulic valve bank

5. Test Bench Assembly and Programming

This chapter discusses the assembling of the selected hardware on a test bench for testing before installing on the shovel. This is required to make sure the normal operation of the machine is not hampered by the use of new hardware. Also included in this chapter is the programming of the PLC to communicate with the hardware and control computer software to implement the control architecture.

5.1. Hydraulic Pilot pressure Characteristics of Hitachi EX3500

The operation of the Hitachi shovel will not drastically change after the electro-hydraulic conversion. The electro-hydraulic valves should behave in the same way as the mechanical pilot system currently being used on the shovel. That is to say, for a given joystick input, the output pressure for the electro-hydraulic pilot valves should be the same pressure as the mechanical system. In order to confirm this, the output pressure characteristics of the mechanical pilot valves on Hitachi EX3500 shovel were measured. This was done at the Phoenix Mine by measuring the output pressure from the pilot valves while holding the each joystick in a series of positions with the machine moving. These measurements are shown in Table 1 and graphically in Figure 23. The communication controller will be programmed in a way to adjust the valve control signals to electro-hydraulic valves so that they deliver similar output pressures when installed on the shovel.

Joystick Angle (Degrees)	Pilot Valve Pressure (psi)		
	Boom	Arm	Bucket
0	80	80	80
4	80	80	80
9	220	220	210
15	320	350	310
20	420	420	390
25	740	740	740
30	740	740	740

Table 1: Pilot valve pressures for Hitachi EX3500 Shovel

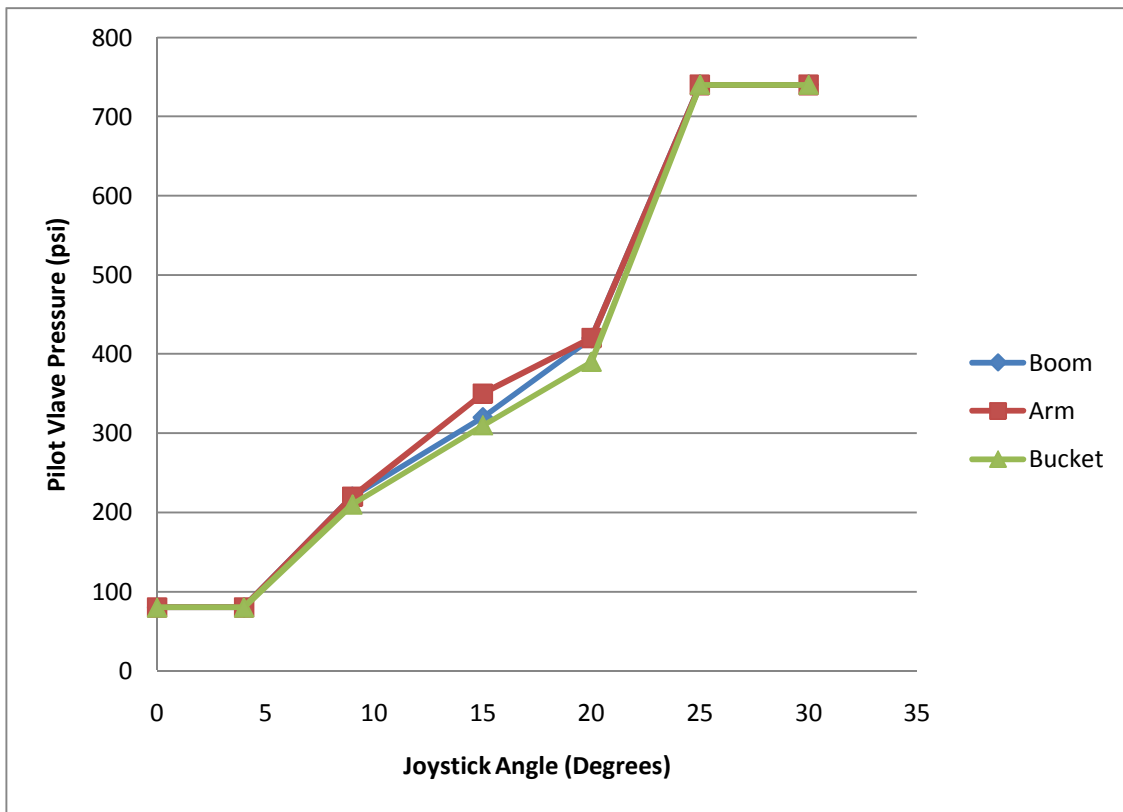


Figure 23: Pilot valve pressure characteristics for Hitachi EX3500 Shovel

5.2. Testing of Electro-Hydraulic Valves

A test bench has been designed and assembled to test the hardware before it is installed on the shovel. The test bench consists of electronic joystick and electro-hydraulic valve bank connected to the communication controller. To test the working of valve bank, a variable hydraulic pressure pump, hydraulic oil tank, a pressure relief valve and an electric motor was installed in the test bench. A constant pressure of 800 psi, corresponding to the pressure supplied to the hydraulic pilot valves on the shovel, is supplied to the pilot port of the electro-hydraulic valve bank. This test bench is shown schematically in Figure 24, and the assembled test bench (worked with Carr (2008) for the test bench assembly) is shown in Figure 25.

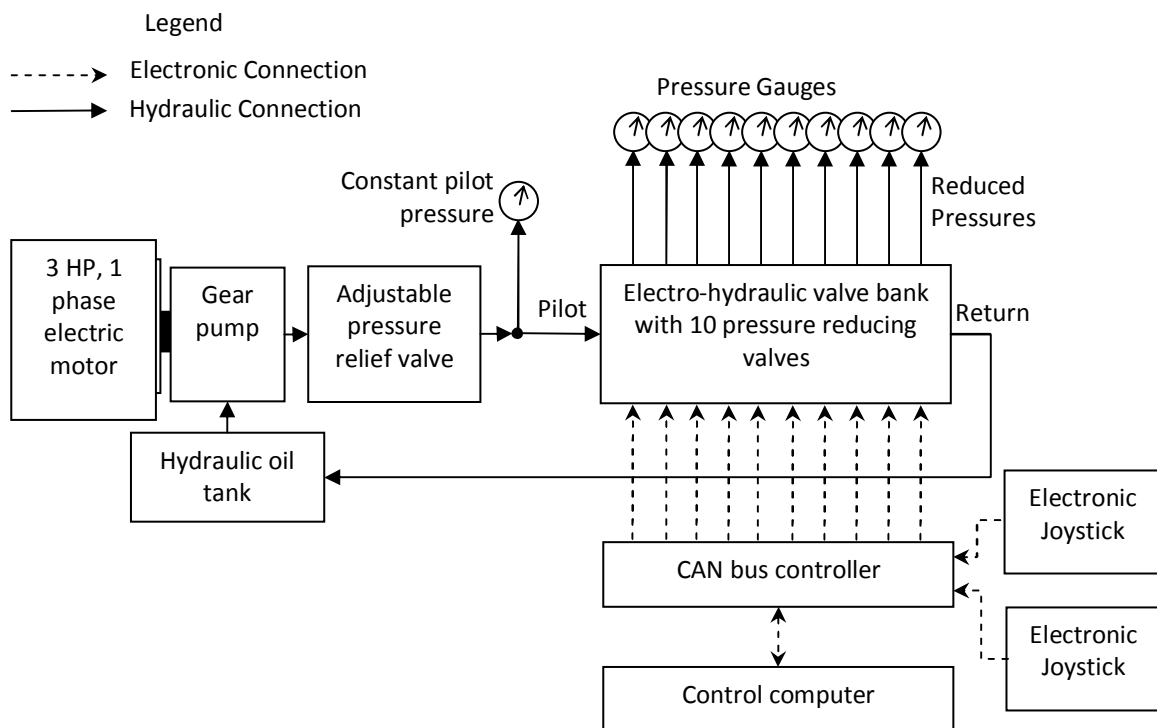


Figure 24: Schematic diagram of test bench configuration

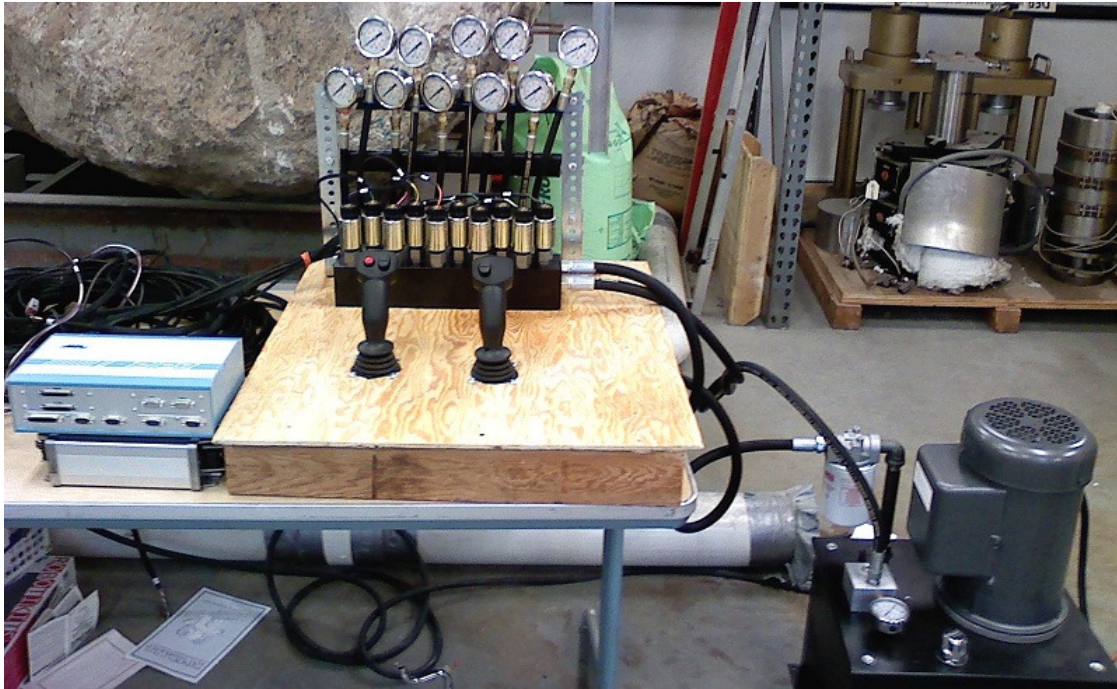


Figure 25: Assembled test bench including all hardware to be tested

The communication controller was programmed to simply pass the input joystick signals to the valve bank after converting them as PWM signals. The test bench was operated with one joystick function at a time and at a given angle of deflection. The reduced output pressures from the electro-hydraulic valves were recorded for each joystick position, using the pressure gauges attached to each valve. The successful control electro-hydraulic valves using electronic joysticks confirmed the feasibility of installing the selected hardware on the Hitachi EX3500 shovel. A detailed explanation of these test results is given in chapter 6 of this thesis.

5.3. Communication Controller Programming

The communication controller used in the hardware design is a programmable logic controller (PLC). This PLC is used to perform the data acquisition and valve control for the control system. All the input and output control hardware is connected to the communication controller. The electronic joysticks and the rotary encoder are connected to the controller through a CAN bus nodes. The joystick connection uses CAN J1939 protocol where as rotary encoders are connected using CAN OPEN protocol. The electro-hydraulic valve bank is connected to the digital outputs of the communication controller which can be programmed to use as PWM outputs. The control computer can be connected to the controller through a USB port connection. In order to communicate with all these hardware, the communication controlled needs to be programmed. The programming software used for this is PROSYD 1131, specially designed software to program the DIGSY Compact controllers.

The electro-hydraulic valve control can be obtained in two different modes. In manual mode, the communication controller sends joysticks signals directly to control the valves without turning ON the control computer. If robotic-assisted operation is desired, the control computer must be turned ON in order to activate the motion control software. In this robotic-assisted control mode, the communication computer sends the input joysticks signals to the control computer instead of directly sending to the valves. The control computer uses the input signals along with position sensor signals to execute the control software and generates the valve control signals. These

control signals will be sent to the communication controller, which converts them to PWM signals to be sent to the electro-hydraulic valve bank. The connection diagram of the electro-hydraulic machine controller in manual and robotic-assistance mode is shown schematically in Figure 26. A mode selection switch will be used to select the mode of operation.

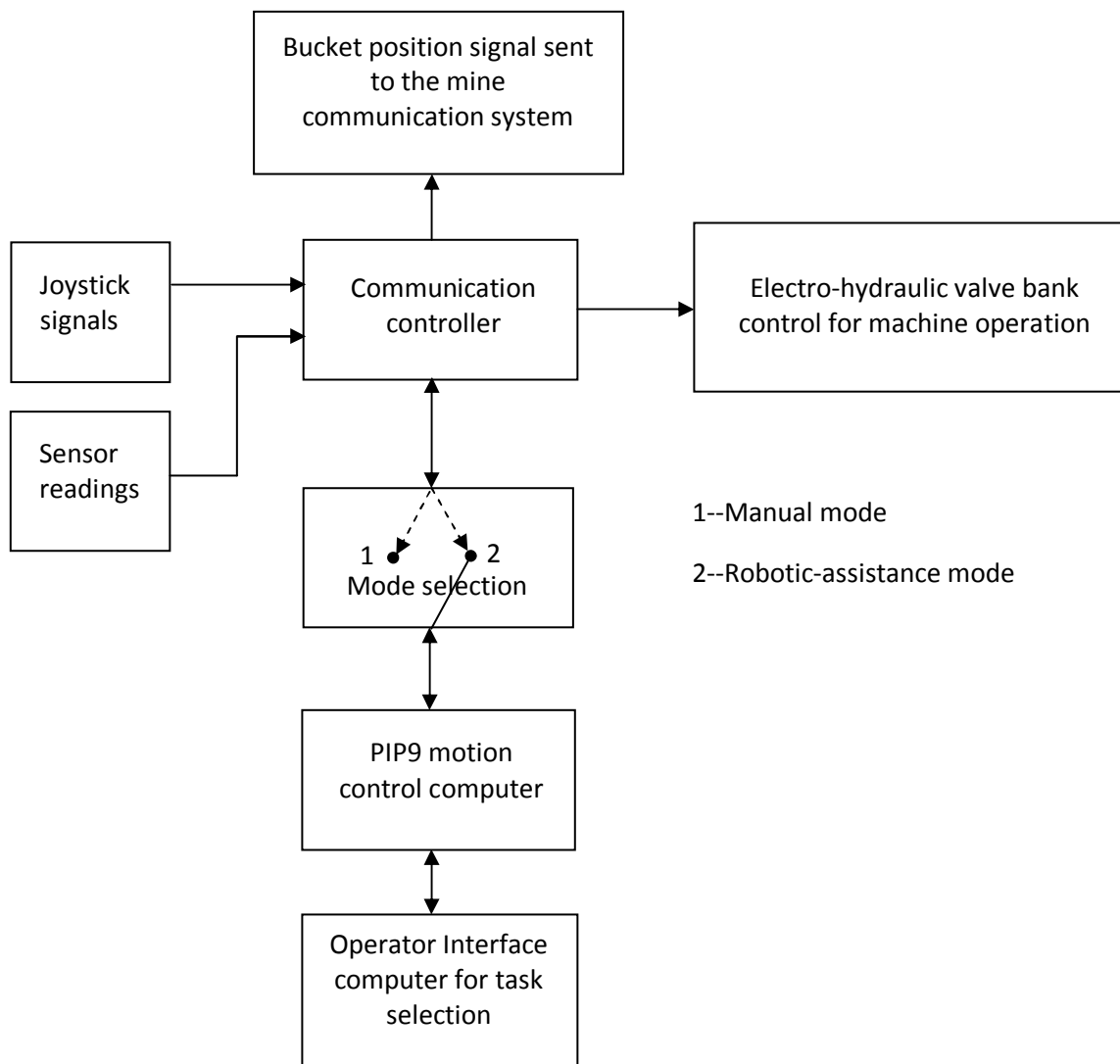


Figure 26: Schematic diagram of electro-hydraulic machine controller

5.3.1. Electro-Hydraulic Valve Control in Manual Mode

In the scope of this thesis work, the communication controller was programmed and the electro-hydraulic valve control has been tested in manual mode operation. The two electronic joysticks used in the design are multi-axis control devices. Each joystick is assigned with specific machine control functions. The right joystick in X-axis is used to control the boom up and down, and in Y-axis, controls the bucket in and out. The left joystick in X-axis controls the arm in and out where as in Y-axis controls the slew right and left. The rocker switch on the right joystick controls the bucket open and close function. A PROSYD1131 software program is developed for communication controller to assign each of the input signals from the 5 machine functions to the corresponding valves in the electro-hydraulic valve bank. Figure 27 shows a controller program in PROSYD1131 software to control the valve bank using joystick input.

The communication controller receives input data through CAN bus corresponding to the degree of deflection of the each joystick in particular direction. The output signal from each joystick is an 8-bit digital data (0-255). The controller converts this digital data into 10-bit pulse width modulated signals (0-1023). These PWM control signals are then supplied to the electro-hydraulic valves to control the pressure output. The connection diagram of electro-hydraulic machine controller in manual mode is shown in Figure 28. In the current configuration, the controller is operating at a speed of 100 Hz, which means for every 10 milliseconds the communication controller updates the valve control signals.

0001	JR X Pos(%MB1661) = 0		
0002	Output_1(%QW19) = 0		
0003			
0001	CLLI_Manager();		
0002	CAN_Manager();		
0003	QP_Start:=255; (* To enable all PWM outputs*)	QP_Start = 255	
0004			
0005			
0006	(*TO SEND JC MOVEMENT TO CORRESPONDING VALVE*)		
0007	(*RIGHT JOYSTICK (JR) CONFIGURATION*)		
0008			
0009	IF JR_X_Right=1 (*CHECK FOR JR RIGHT HAND SIDE MOVEMENT*)	JR_X_Right = FALSE	
0010	THEN		
0011	Output_1:=REAL_TO_WORD(JR_X_Pos * 4.092); (*syntax for Joystick	Output_1 = 0	JR_X_Pos = 0
0012	ELSE		
0013	Output_1:=0;	Output_1 = 0	
0014	END_IF;		
0015			
0016	IF JR_X_Left=1 (*CHECK FOR JR LEFT HAND SIDE MOVEMENT*)	JR_X_Left = FALSE	
0017	THEN		
0018	Output_2:=REAL_TO_WORD(JR_X_Pos * 4.092); (*syntax for Joystick	Output_2 = 0	JR_X_Pos = 0
0019	ELSE		
0020	Output_2:=0;	Output_2 = 0	
0021	END_IF;		
0022			
0023	IF JR_Y_Right=1 (*CHECK FOR JR FORWARD MOVEMENT*)	JR_Y_Right = FALSE	
0024	THEN		
0025	Output_3:= REAL_TO_WORD(JR_Y_Pos * 4.092);	Output_3 = 0	JR_Y_Pos = 0
0026	ELSE		
0027	Output_3:=0;	Output_3 = 0	
0028	END_IF;		
0029			
0030	IF JR_Y_Left=1 (*CHECK FOR JR BACKWARD MOVEMENT*)	JR_Y_Left = FALSE	
0031	THEN		
0032	Output_4:= REAL_TO_WORD(JR_Y_Pos * 4.092);	Output_4 = 0	JR_Y_Pos = 0
0033	ELSE		
0034	Output_4:=0;	Output_4 = 0	
0035	END_IF;		
0036			
0037	(*LEFT JOYSTICK (JL) CONFIGURATION*)		
0038			
0039	IF JL_X_Right=1 (*CHECK FOR JL RIGHT HAND SIDE MOVEMENT*)	JL_X_Right = FALSE	
0040	THEN		
0041	Output_5:= REAL_TO_WORD(JL_X_Pos * 4.092);	Output_5 = 0	JL_X_Pos = 0
0042	ELSE		
0043	Output_5:=0;	Output_5 = 0	
0044	END_IF;		
0045			
0046	(*RightsideCPU-SLAVE*)		
0047	Right_QP_Start:=255;	Right_QP_Start = 255	
0048			
0049	IF JL_X_Left=1 (*CHECK FOR JL LEFT HAND SIDE MOVEMENT*)	JL_X_Left = FALSE	
0050	THEN		
0051	Right_QP1_1_Output:= REAL_TO_WORD(JL_X_Pos * 4.092);	Right_QP1_1_Output = 0	JL_X_Pos = 0
0052	ELSE		
0053	Right_QP1_1_Output:=0;	Right_QP1_1_Output = 0	
0054	END_IF;		
0055			
0056			
0057	IF JL_Y_Right=1 (*CHECK FOR JL FORWARD MOVEMENT*)	JL_Y_Right = FALSE	
0058	THEN		
0059	Right_QP1_2_Output:= REAL_TO_WORD(JL_Y_Pos * 4.092);	Right_QP1_2_Output = 0	JL_Y_Pos = 0

Figure 27: Controller program in PROSYD1131 software

In the manual mode, the controller also receives the sensor readings from rotary encoders. These sensor signals provide the angular position of each of the machine link. This data can be used to calculate the precise bucket position which is useful in ore grade control. This task is not completed yet and should be fixed in future work.

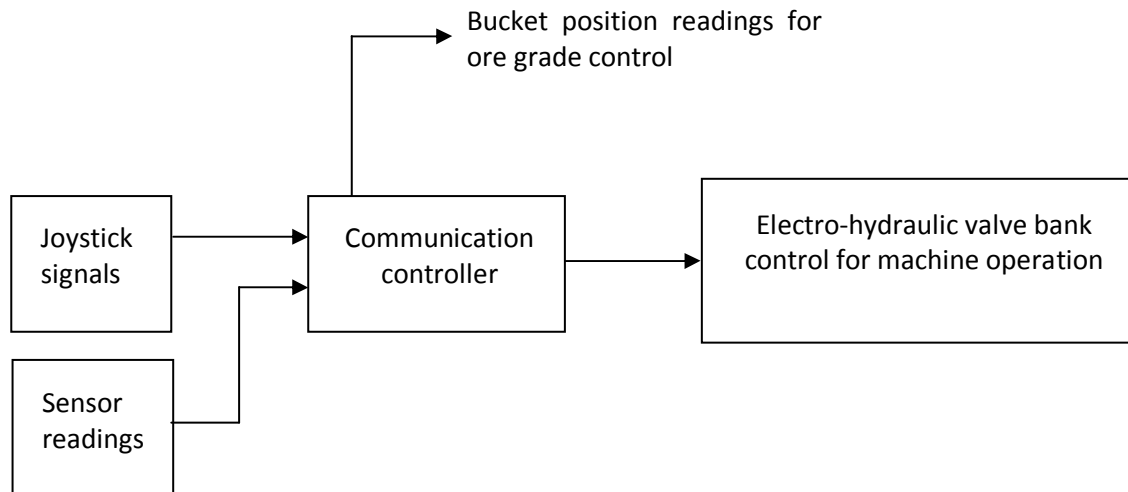


Figure 28: Schematic diagram of electro-hydraulic machine controller in manual mode.

6. Results and Discussions

The test bench described in the previous sections has been tested and manual control of electro-hydraulic valves was demonstrated. The output pilot pressures from the valve bank are measured and compared with the pilot pressures from hydraulic valves in the Hitachi EX 3500 machine. The response speed of the system for joystick input is determined. The test results are presented and efficiency of the control architecture is discussed in this section.

6.1. Electro-Hydraulic Pilot Pressure Characteristics

To confirm that the behavior of Hitachi EX 3500 excavator will not change drastically with the installation of electro-hydraulic system, the pilot pressures from the electro-hydraulic valves on the test bench are measured and compared with the valve pressures measured on the shovel (the hydraulic pressure characteristics of Hitachi EX 3500 are discussed in section 5.1). The electro-hydraulic valve bank is tested at two different pressures supplied to the pilot port. During the first test, the valve bank is supplied with a constant pressure of 640 psi and the output pilot pressures are measured with holding each joystick at different positions. The results of these measurements are shown in Table 2 and Figure 29. The test is repeated by increasing the pilot port pressure to 800 psi and the test results are shown in Table 3 and graphically in Figure 30.

These test results show that the electro hydraulic valve control in manual mode is similar to the normal, manual control of the Hitachi EX 3500 shovel. The hardware

modifications can be installed on the shovel to make the operation more intuitive and faster with the electronic control.

Joystick position	Pilot pressure (psi)
0	20
20	45
40	150
60	280
80	400
100	500
125	640
150	640
175	640
200	640
225	640
250	640

Table 2: Electro-hydraulic pilot valve pressures at 640 psi pilot pressure

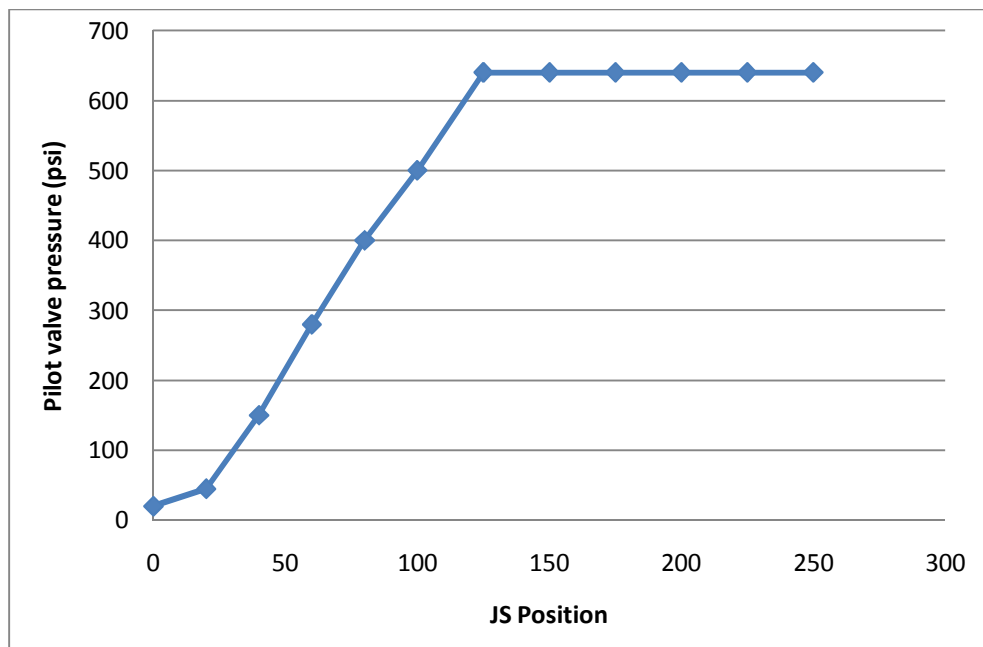


Figure 29: Electro-hydraulic pressure characteristics at 640 psi pilot pressure

Joystick position	Pilot pressure (psi)
0	80
25	100
50	220
75	380
100	520
125	620
150	780
175	780
200	790
225	790
250	790

Table 3: Electro-hydraulic valve pressures at 800 psi pilot pressure

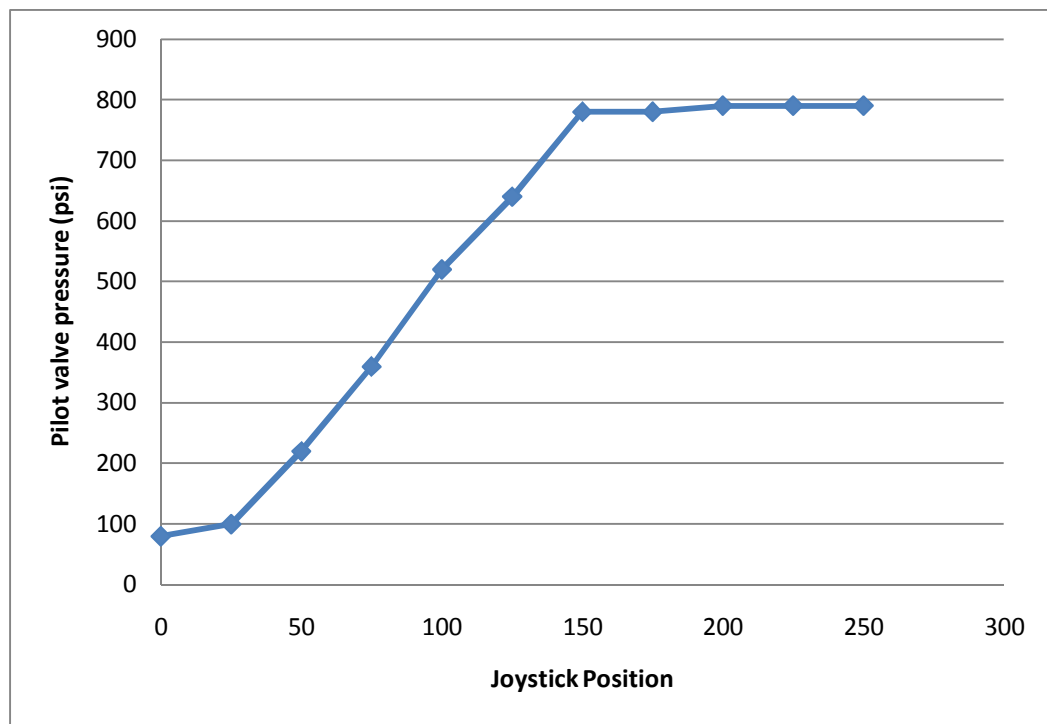


Figure 30: Electro-hydraulic pressure characteristics at 800 psi pilot pressure

Figure 31: Output pressure characteristics

6.2. Valve Response Characteristics

Valve response time to input joystick movement is an important parameter in terms of system speed. In order to measure the response time of electro-hydraulic valve bank, a simple test was conducted. In this test, a micro switch is attached to one side of the joystick. A pressure transducer that gives voltage output is used to measure the pilot valve pressure from one valve. The joystick is moved by holding the push button switch to open/close the corresponding valve. The response of the switch and pressure transducer are recorded using an oscilloscope. Since the micro switch is attached to the joystick and moved together, the switch response time can be considered as the time at which joystick input is applied. The waveform data from oscilloscope is recorded and plotted as shown in Figure 32. This test is repeated several times and the average response time of electro-hydraulic valve bank to joystick input is observed as 210 milliseconds.

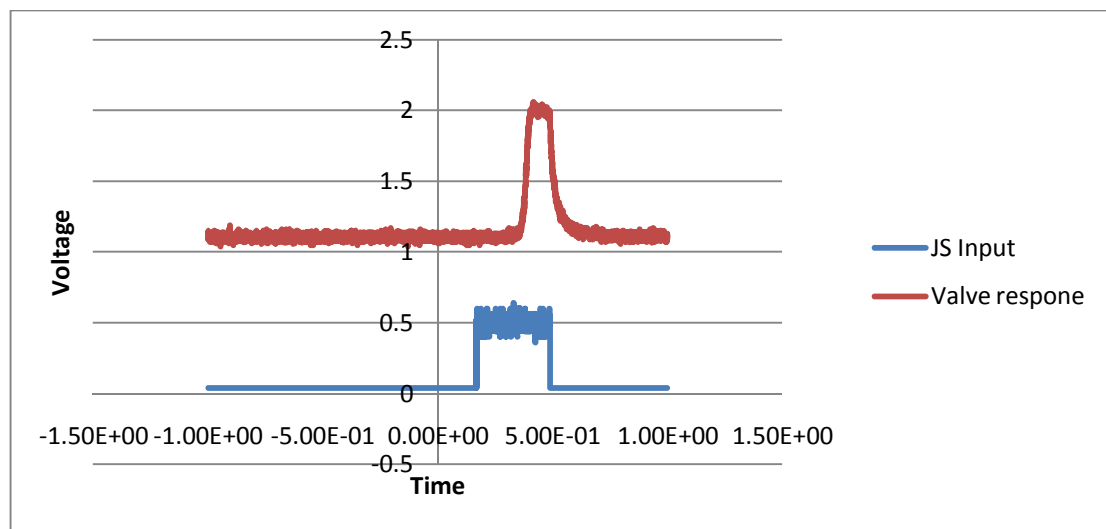


Figure 32: Valve response characteristics

6.3. Effect of Temperature Changes on Output Pressure

The temperature of the oil in the hydraulic reservoir generally increases when the system is operated for long periods of time. The electro-hydraulic valve control should be stable with change in oil temperature in the hydraulic tank. In order to check the stability of the system to deliver similar output pressures at different temperatures, a test was conducted. In this test, initially the oil temperature is maintained at 25 °C and the output pressures from the pilot valves are measured and recorded by holding joystick at various positions. Then the temperature of the oil is raised to 35 °C and output pressures are measured for same joystick input signals. Finally, the test is repeated at oil temperature of 50 °C. Table 4 and Figure 33 show the output pressures at different temperatures. These test results show that the variations in the valve pressures are minimum and acceptable.

JS position	Pilot valve pressures (psi)		
	T1 = 25 °C	T2 = 35 °C	T3 = 50 °C
0	80	70	70
25	100	100	80
50	220	200	170
75	380	340	320
100	520	480	450
125	620	580	580
150	780	760	730
175	780	760	730
200	790	770	730
225	790	770	730
250	790	770	730

Table 4: Output pressure at different temperatures

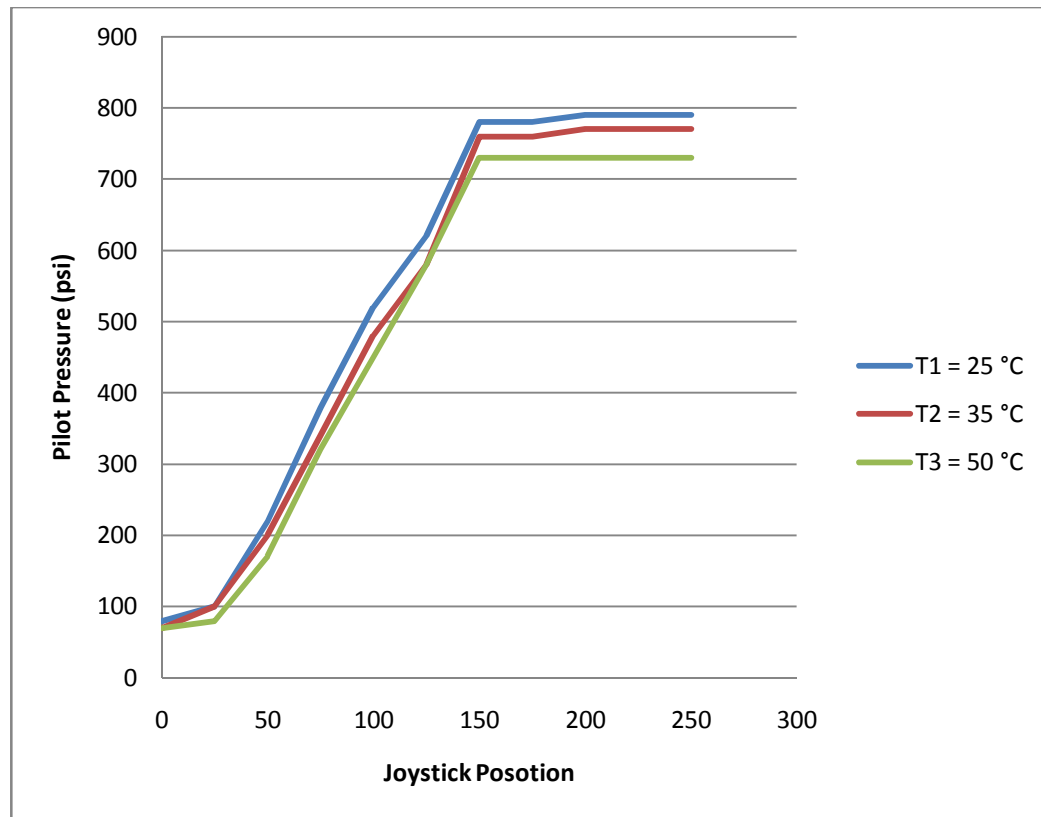


Figure 33: Output pressure characteristics at different temperatures

6.4. Rotary encoder testing

In order to test the accuracy of the rotary encoder, a simple test was conducted. In this test, the shaft of the encoder was rotated by hand and the angle of rotation of the shaft was measured using a protractor manually. The angle of rotation from the communication controller is also recorded. The test was repeated for different angles of rotation of the encoder shaft. The results of this test are shown in Table 5 and graphically in Figure 34. From the results it can be seen that the angle rotation read by the communication controller is very close to the actual rotation of the sensor shaft.

Shaft rotation (degrees)	Encoder Output (degrees)
45	45.087
90	90.043
135	135.087
180	180.132
225	225.087
270	270.043
315	315.087
360	359.956

Table 5: Rotary encoder test results

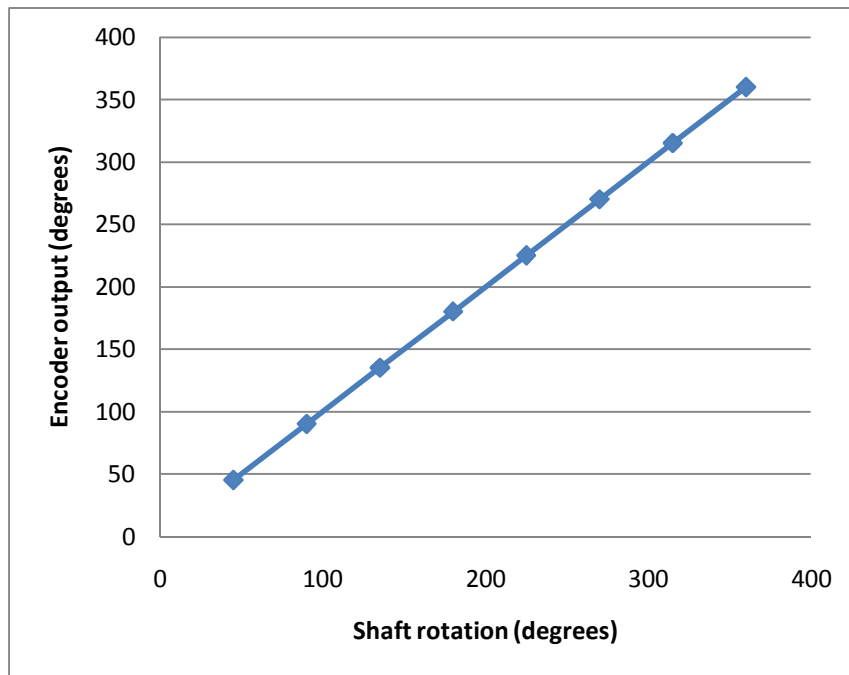


Figure 34: Rotary encoder test – shaft rotation Vs encoder output

7. Conclusions and Recommendations for Future work

In this thesis, the feasibility of implementing computer-assisted control system on a large mining shovel is tested. A hardware modification plan was developed to install the control system on a Hitachi EX 3500 mining shovel. The hardware required to convert the hydraulically operated shovel in to electro-hydraulic control has been tested in a laboratory setting. The application this technology to large mining shovels and excavators is shown to be possible with these hardware modifications. The test results show that with computer-assisted control, energy and time efficiency benefits can be achieved by making the machine operation more intuitive and easier.

7.1. Recommendations for future work

The research presented in this thesis has demonstrated that, it is feasible to implement the previously developed computer-assisted control on large mining shovels using the commercially available components. Several recommendations for further investigation of the control system installation are given here.

In the next phase of the project, the communication controller has to be programmed to transfer position data from the sensors to the mine communication system. This data transfer is needed for determining the precise location of the bucket relative to the base of the excavator for robotic-assisted control operation. As an extended benefit, the bucket location will be much more accurate when determined from the sensors on the bucket, arm, and boom than from the estimate using cab rotation based on GPS signal alone. Therefore, the more accurate bucket position (that

will be needed for machine control anyway) will be made available for ore grade control application.

Before installing the hardware modifications described in this thesis on Hitachi shovel, the safety of valve control operation needs to be tested and a safety monitoring system has to be designed to activate a alarm during possible malfunctions such as lost cable connections, lost power supply etc.

7.1.1. Installation on Hitachi EX 3550 Shovel

Installation of control system on the Hitachi EX 3500 shovel will be carried out in two stages. During the first stage, the hardware should be installed on the shovel. This will include the installation of the communication controller, the electronic joysticks, the electro-hydraulic valves and the rotary encoders. It should first be confirmed that normal operation of the machine is not hampered by the use of these new hardware. The operation of the machine with new hardware should be observed for several months to make sure that the shovel operation is normal and smooth.

In the second stage, an onboard computer with robotic control software will be connected between the human input devices (joysticks) and the electro-hydraulic system of the machine.

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