Ph.D. Topic Proposal:

Haptic Control of Hydraulic Machinery using Proportional Valves

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ABSTRACT

Applying haptic or force feedback to hydraulic machinery such as excavators has the potential to increase operator capabilities. Haptic robotic human-machine-interfaces enable several enhancing features including: coordinated motion control and programmable haptic feedback. Coordinated or resolved motion control supplies a more intuitive means of specifying the equipment’s motion. Haptic feedback can be used to relay meaningful information back to the user in the form of force signals. This adds to the cost of the product by increasing the number of sensors, the required computing power and the complexity of the human-machine-interface. In order to make this technology economically viable, the benefits must offset the additional cost associated with implementation.

One way to offset this cost is to not use high-end hydraulic components. The tractor mounted backhoe used in this research uses low-end components including: a constant displacement pump, proportional valves and pressure sensor based force estimation. All of these items tend to limit system performance. Characteristics that limit the performance of the system include: valve spool bandwidth, valve dead-band, delay and noisy force estimation from pressure sensors. Stability is also an issue. An advanced haptic control technique, similar to ones used to deal with time-delayed teleoperation, will be used to maintain stability during haptic teleoperation. Modeling and control of the real test-bed will then be used to develop a virtual excavator for human-in-the-loop testing. Using a virtual model for human testing is desirable from a safety point of view and allows for key parameters to be varied instantaneously. This tool will be used to measure the enhancement in operator control and evaluate the limitations due to system characteristics such as valve dead-band and bandwidth. Use of this virtual excavator will be designed to enhance testing on the real machinery rather than replace it. Not only will the virtual simulator be modeled after HEnRE, but the control algorithm used in the simulator will be tested on the actual hardware. The end-goal of this project is to incorporate haptic control algorithms that work on low-cost systems and maximize the enhancement of operator capabilities.
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1 INTRODUCTION

The addition of haptic feedback to human operated hydraulic machinery can improve productivity and dexterity by relaying information back to the user. Using a robotic human-machine-interface allows the haptic feedback to be programmed in order to display meaningful forces to the operator. These signals could be used to reflect the limitations of the machinery or the forces acting on the end effector. Electronic joysticks and manual levers are the standard methods used to manipulate mobile hydraulic machinery such as excavators. Both of these incorporate haptic feedback; however, it is limited and is not programmable. Traditional manual levers reflect some forces from the line pressure due to their direct coupling to the hydraulic system. Both manual levers and electronic joysticks have some haptic feedback from a restoring spring force which is directly related to their displacement and the commanded velocity of the manipulator. In the case of electronic joysticks this haptic feedback is inherently decoupled from the system being controlled. This means that the human machine interface is unilateral since information signals are only flowing from the human to the remote manipulator. This forces operators to rely on other cues such as vibrations and audibles. If a haptic display is used, the human machine interface becomes bilateral and information can also flow back to the operator from the end-effector via haptic feedback.

The goal of this research is to explore how haptic feedback can be applied to control cost effective hydraulic systems. This means the system being studied has a constant displacement pump and open centered valves. The primary test-bed is a tractor-mounted backhoe excavator. A constant displacement pump supplies flow proportional to engine speed and open center valves allow flow through the valves with minimal pressure loss when flow does not need to be diverted to the actuators.

The alternative is to use a variable displacement pump. Variable displacement pumps supply the system with a near constant pressure and flow as required. This type of pump improves system performance at a price and is usually only found on higher end (i.e. larger and more expensive) excavators. The higher end valve equivalents are known as servo valves. These valves offer high bandwidth and use tight tolerances to prevent internal leakage while minimizing dead-band. A lower cost alternative to servo valves are proportional directional control (PDC) valves. These valves have slower dynamics and more dead-band to prevent internal leakage and avoid high cost, high precision machining. Since PDC valves are closed center, there must be an additional open-center pressure regulating valve that diverts flow to the closed center PDC valves. In other words, the pressure regulating valve throttles the main flow to create the pressure needed to operate the closed center PDC valves. The main pressure regulating valves are not needed if the PDC valves are used with a variable displacement pump. Unfortunately, the combination of dead-band and slow valve dynamics limits the performance of these valves, since the main spool must move through the dead-band in order to
change the direction of the flow. This performance is degraded even more because of the delay associated with the pressure building up in the main pressure regulator. This research will address issues and limitations associated with applying haptic control to hydraulic systems controlled by proportional directional control valves.

2 BACKGROUND

2.1 Haptics

The first modern teleoperators were created by Goertz at Argonne National Labs([11] as cited by Sheridan [60]). This electrically operated teleoperator was designed to replace mechanical master-slave manipulators [10] being used to handle dangerous radioactive material. Due to the identical master and slave manipulators, the system was able to reflect the forces acting on the slave back to the human operator grasping the master. Due to the advantages associated with using hydraulically actuated slaves, the nuclear industry also experimented with totally hydraulic force reflecting master-slave manipulators [21]. Today electro-hydraulic valves allow for electrically controlled, hydraulically actuated remote manipulators. How to best reflect and display force signals remains an active area of research.

Most of the theory associated with haptic feedback originated from active network theory [17, 30]: energy variables or effort-flow combinations(i.e. voltage-current, force-velocity, etc), impedance/admittance [18, 19, 20], two-port networks [13, 52], absolute stability (Llewellyn Stability Criterion) [40] and passivity [6, 15, 28]. Enabled by modern computing power, these concepts are used to create haptic interfaces that can reflect forces from virtual and remote environments.

Two conflicting goals of force reflecting teleoperation is that it is desirable to have low force during free, unconstrained motion and stable interaction with stiff environments. A system’s damping affects both of these goals [14]. Low damping allows the force displayed to the human to be small during free motion. High damping is desirable during contact with stiff environments because it damps out oscillations and dissipates energy that could otherwise destabilize the system.

Hannaford [13] proposed adapting the impedance control law based on an estimation of environment impedance. Salcudean et al. [58] implemented Hannaford’s bilateral matched impedance on a mini-excavator. It is called bilateral match impedance control because both the remote environment and the human’s impedances are estimated on-line and used to adjust the impedance of the opposite device. Love and Book developed and implemented a different adaptive impedance control [41, 42] strategy. This controller used a learning routine to estimate the environmental impedance as the manipulator moved through
the workspace. This allows the damping (i.e. stability margin) to be reduced after a lower, less conservative environmental stiffness estimation was found.

Another way to adapt a haptic network’s impedance is to monitor a system’s passivity or flow of energy. This method was first applied to time-delayed teleoperation [48, 73]. A similar concept called Time-Domain Passivity was proposed by Ryu and Hannaford [15] to optimize the damping in haptic interfaces coupled to virtual environments. This method’s name came from the fact that it is derived from the time-domain definition of passivity [61](Equation 1).

\[
\int_{0}^{t} (y_{1}(\tau)u_{1}(\tau) + \cdots + y_{n}(\tau)u_{n}(\tau))d\tau > \alpha, \exists \alpha > -\infty, \forall \ t \geq 0
\]  

The inputs, \( u_{i}(t) \), and outputs, \( y_{i}(t) \), are energy variable pairs so the sum of their products represent power flowing into the system. Integrating this sum represents the net flow of energy into the system. If the system is passive this value is bounded by the initial energy store in the system \( \alpha \).

When the system becomes non-passive, the damping of the master can be increased. Essentially, this acts to dissipate the energy being introduced into the system by the human operator. More importantly, the energy exerted by the slave onto the environment can also be limited. This is often a more practical method to enforce the passivity of the overall system. Using this method helps the transparency of the teleoperator because it reduces force during free motion. It has been shown through human factors testing that higher damping during contact with stiff environments can not only improve stability, but also improve the perceived stiffness of the object [32].

Time-domain passivity was extended to teleoperators by Ryu et al. [57] and general control systems [56]. Kanaoka and Yoshikawa also proposed using a passivity monitor to guarantee global stability of an arbitrary robotic manipulator during free and constrained motion. This method requires that that robot be asymptotically stable during free motion and works using the same basic concept as time-domain passivity. A similar technique has also been developed by Lee and Li [34]. These methods are similar to Love and Book’s adaptive impedance control in the sense that they limit the energy exerted, by the system. The difference is that adaptive impedance control is based on spatial learning and the other techniques are based on the flow in energy in and out of the system and the concept of passivity.

### 2.2 Robotic Excavators

Some of the first researchers to propose the application of force feedback to hydraulic systems such as excavators were Starzewski and Skibniewski [50]. They predicted enhancements due to coordinated motion and “feel” or haptic feedback that could be provided by such an interface. This concept paper concluded by
predicting the commercial use of such systems when it was technically and economically feasible. Like many other roboticists with an interest in excavators, their research turned toward autonomous robotic excavators that could work independently of humans instead of with humans [12, 25, 35, 63, 69]. Others in academia [3, 29, 59, 67] and the nuclear industry [1, 2, 5, 22] have focused on teleoperation of excavators with various levels of haptic feedback.

Using a haptic robotic human-machine-interfaces offers several possible enhancements other than force reflection. These devices enable coordinated motion control and the ability to program virtual fixtures [27, 53] into the workspace. Coordinated control is a subtle, but a profound improvement over conventional hand controllers that work in joint space. Using joysticks that individually control the joints of the manipulator puts a “high perceptual and psychomotor demand” on the operator [70, 71]. Using coordinated motion control and a single hand controller whose motion corresponds directly to the slave manipulator reduces this mental load by doing the inverse kinematics for the operator. Human factors tests done using human-in-the-loop experiments indicate: improved accuracy, better or equal completion times and decreased training time for novice users [71]. Experiments done on a log loader were also conducted using 10 novice and 6 expert operators [70]. As expected, the novice operators perform better using the coordinated controller, while the expert operators perform better using the joint controller due to years of experience. However, the expert’s performance on the two controller were converging as the testing concluded after six days. This implies that the expert operators could be just as proficient on the new controllers in a relatively short period of time. Experienced operators also expressed positive comments on the new hand controllers.

Usually, force reflection is defined and evaluated in terms of transparency. Transparency in a property that describes how accurately a haptic interface can display the forces from a virtual model or a remote environment. A simple mathematical explanation for transparency can be given by looking at two-port network parameters that describe a system. A two-port network can describe the relationship between teleoperator’s inputs and outputs. The subscripts \( h \) stands for hand or human and the subscript \( e \) stands for end-effector, environment or exogenous force. The variables \( V \) and \( F \) are velocity and force respectively. \( Z_{in} \) is the impedance of the input haptic interface and \( Z_{out} \) is the impedance of the remote manipulator.

\[
\begin{bmatrix}
F_h \\
-V_e
\end{bmatrix} =
\begin{bmatrix}
h_{11} & h_{12} \\
h_{21} & h_{22}
\end{bmatrix}
\begin{bmatrix}
V_h \\
F_e
\end{bmatrix}
\]

(2)

\[
\begin{bmatrix}
h_{11} & h_{12} \\
h_{21} & h_{22}
\end{bmatrix} =
\begin{bmatrix}
Z_{in} & Force\ Scale \\
Velocity\ Scale & Z_{out}^{-1}
\end{bmatrix}
\]

(3)
The system is “Perfectly Transparent” if and only if the following holds.

\[
\begin{bmatrix}
F_h \\
-V_e
\end{bmatrix} = \begin{bmatrix}
0 & 1 \\
-1 & 0
\end{bmatrix} \begin{bmatrix}
V_h \\
F_e
\end{bmatrix}
\]

(4)

It has also been shown that a perfectly transparent teleoperator is impossible to achieve without limitations on bandwidth [31]. However, transparency is still an ideal for which many haptic research have strived to achieve. A less strict definition of transparency also includes spatial and power scaling factors. Transparency is most intuitive when position mode is used because the network is simply making the force and movement from each side correspond. A rate control version of transparency has also been defined were slave velocity is the integral of the haptic interface’s velocity and the force exerted on the operator’s hand is the derivative of the force the environment exerts on the slave manipulator [16].

In the case of haptic control of hydraulic equipment a more practical, albeit more abstract, measure of force reflection is the enhancement to human performance. The only way to measure this is through human factors testing [70, 71]. One such force reflecting architecture was proposed by Parker et al. [51]. This controller uses a rate mode strategy, but does not use the traditional rate mode force reflection where the incoming force signal is differentiated. Instead it adjusts the stiffness of the hand controller’s spring based on the forces acting on the manipulator. The equation for this spring is given in Equation 17 in Section 4.5.

2.3 Non-Ideal Features of Hydraulic Systems

While hydraulic systems offer a practical application of haptic feedback, their characteristics are detrimental to the implementation. In the case of proportional directional control valves these characteristics include nonlinear valve orifice coefficients, delay, dead-band and slow dynamics. Research exploring autonomous excavator operation share these challenges. One solution to the problem is to buy higher cost hydraulic components. This was the solution used by Ha et al. [12] where the excavator’s manual valves were replaced with servo valves. Other researchers used the open center systems with proportional valves [22, 35, 59]. All of these researchers had to put up with the slower response and dead-band in these systems. Slow spool response and dead-band are an issue when the spool starts from its centered position or has to move through its dead-band to change the direction of the valve’s flow. Other modifications to the systems have also been tried. Lawrence et al. experimented with a system that used multiple variable displacement pumps to control individual actuators [33]. Tafazoli et al. created a custom differential PWM pilot stage that could move the spool faster in order to minimize the effect of the dead-band [65].

Significant dead-band is a characteristic of many lower quality proportional valves suitable for use in
excavators. Servo valves have much smaller dead-band due to their tight tolerances. Using tight tolerances allows the valves to prevent leakage with only a small overlap. However, the precision machining required to do this increases the overall cost of the valve. Proportional valves prevent this leakage with an overlap that can account for as much as thirty percent of the spool’s travel [35]. Dead-band can limit the system’s performance because high gains will cause a limit cycle with closed-loop control. This can be shown by describing function analysis of this problem [38]. One way to get around this problem is to use a dead-band inverse. In the case of a servo valves with fast dynamics this can be achieved with good performance [8]. In the case of a proportional valves the effectiveness of the dead-band inverse is limited by the dynamics of valves [39, 68]. This is due to the dead-band nonlinearity being sandwiched between the spool dynamics and the dynamic of the rest of the hydraulic system [68]. The inverse dead-band is located at the input and essentially corrects the desired spool position; however, the limitation on how fast the spool can move determines how fast the desired spool position can be achieved. In turn, this limits how well the system can track a desired trajectory. The valve modification by Tafazoli et al. essentially reduces the effect of their spool’s dead-band by increasing the speed and bandwidth of the spool [65].

Another factor that can limit how fast an open-center system can respond is the rate at which the main system pressure can build up [35]. This is especially true of load-compensated pressure regulators that react to the maximum line pressures of any of the opened valves. This type of design is good from an energy savings point of view, but is detrimental to closed-loop control which is necessary for haptic teleoperation or autonomous operation. The system has to wait in order for pressure to build up when starting from rest and the pressure can drop and may need to build up again when the valve orifices are temporarily closed as the valves changes the direction of the flow. This problem could be minimized by using an pressure regulating valve with an electronically controlled set point. Having to wait for the system pressure to build up also compounds the sandwiched dead-band problem because it reduces the responsiveness of the spool by limiting the pilot pressure.

A low-cost alternative to the proportional directional valve is the poppet valve [39, 49, 74]. Poppet valves are responsive and sandwiched dead-band problem is not a problem. Due to the fact that four or more valves are used to control a single actuator, the system can be more energy efficient, but require more inputs to control the system. Alternatives to proportional directional valves such as multiple poppet valves will not be addressed by this research.
2.4 Hydraulic Control

Before it is possible to do any kind of force reflecting teleoperation, it is necessary to be able to control the remote manipulator’s motion (force) and measure its force (motion). How well this can be done will limit the performance of the teleoperator. Since the hydraulic valves control fluid flow, a controller will be designed to control cylinder motion. One controller design, proposed by Sepehri et al. [59], that can be applied to proportional valves and open-center systems incorporates a nonlinear feedforward term and a PD control law. The line pressures are measured and the desired flow is calculated from the desired cylinder speed. These variables are used to calculate the desired orifice size which corresponds to a desired spool position. It is important that the line pressures are used in this calculation. This feedforward term is used to get the valve close to the desired spool position and the PD term forces the system to track the desired velocity and position. A similar form of this controller was later used by Tafazoli et al. [58, 67] and Johnson et al. [22].

Other excavators have incorporated sliding mode robust control: servo valves [12, 44] and proportional valves [35]. In all of these cases the input had to be modified in order to avoid chatter. Yao et al. applied adaptive robust motion to single-rod actuators using both proportional directional control valves [72] and programmable valves each comprised of five poppet valves [39]. Due to the complex nature of these systems, it is often possible to improve performance by using learning and adaptive control techniques [22, 49, 62]. The concept of passivity, a concept central to many haptic controllers, has been applied to hydraulic valves by Li [36]. Li showed that it is possible to have a hydraulic valve behave passively by either modifying the spool or by using passivity theory and an active control law that passifies the system using an energy storage function. This work has been extended and applied to an excavator like manipulator with guaranteed passive behavior [37].

3 CURRENT LIMITATIONS

Limitations of previous research on haptic control of hydraulic machinery include:

1. Time-domain passivity/passive energy monitoring has not been applied to the teleoperation of nonlinear, low-performance hydraulic systems
2. Time-domain passivity/passive energy monitoring has not been applied to real systems with considerable delay due to dead-band, slow sampling update rates or other sources.
3. Time-domain passivity/passive energy monitoring has not been applied to teleoperators with significant mechanical dissipation.
4. Time-domain passivity/passive energy monitoring has not been applied to a teleoperators using a rate
mode scheme and a force reflecting haptic interface.

5. Sandwiched dead-band dynamics in hydraulic system have not been looked at from a haptics point of view using human factors testing. The affect that spool dead-band and bandwidth has on an operator’s performance using haptic feedback has not been evaluated.

6. Economical force estimation/measurement using pressure measurements is a topic that has received limited attention and only simple viscous-coulomb friction models have been applied.

7. Force-reflecting teleoperation schemes applied to haptic excavators have relied on linearized dynamics at a given set point

4 PROPOSED RESEARCH

The goal of the proposed research is to explore how haptic feedback can be used to enhance operator capabilities in hydraulic equipment using low-cost components offset by advanced controller design. One way to decrease cost is to use proportional valves and an open-center system. This was a theme that guided the construction of this test-bed and the choice of valves for this project. Some of the challenges associated with these valves are valve specific, but many of them such as slow bandwidth, spool dead-band and delay are general to this class of electro-hydraulic valves known as proportional directional control (PDC) valves. The choice of sensors also reflect this theme. For example, line pressures will be used to estimate exogenous forces instead of force sensors. Proposed control strategies also reflect the nonlinearities of this class of systems.

The research plan can be broken into the following tasks.

1. Create the physical test-bed called HEnRE (Haptically ENhanced Robotic Excavator).
2. Create a dynamic model of the HEnRE test-bed.
3. Implement a velocity regulator for HEnRE.
4. Develop a force estimator based on the cylinder pressure readings.
5. Incorporate high-level force reflecting architectures for haptic teleoperation using both rate mode and position mode control strategies.
6. Apply the concept of time domain passivity/passivity energy monitoring to ensure global stability of the combined master-slave manipulators.
7. Implement and test control algorithms on HEnRE.
8. Construct a virtual real-time excavator simulator with a dynamic model of HEnRE, haptic feedback,
visual display, HEnRE tested control system and a soil model with randomly placed, buried objects.

9. Conduct human-in-the-loop experiments to study the effect of valve dead-band and bandwidth on haptic control using the virtual excavator. Do a limited number of human-in-the-loop experiments on HEnRE to use as vallidation for the tests conducted on the virtual excavator.

4.1 Creating the HEnRE Test-bed

![Figure 1: HEnRE and the PHANToM Omni haptic interface.](image)

The primary test-bed that will be used in this research is referred to as HEnRE (Haptically ENhanced Robotic Excavator) [9]. HEnRE is based around a 4410 series John Deere tractor with a Model 47 backhoe and a PHANToM haptic display built commercially by SensAble Technologies. The Model 47 backhoe has been modified. Originally manual valves were the only means available to operate the device. It has been retrofit with Sauer-Danfoss PVE/PVG-32 electro-hydraulic (EH) valves and an array of sensors for feedback control and monitoring. A mechanical valve is used to switch between the original valves and the retro-fitted EH valves. Instrumentation installed on HEnRE includes: position of all four degrees of freedom (swing, boom, dipper-stick and bucket), capside and rodside pressure, main supply pressure, load-sense pressure, main pump flow and inlet oil temperature. The control software for the backhoe is based on Mathwork’s xPC target. This real-time control software interfaces with another computer controlling the PHANToM via ethernet cable using UDP protocol. PHANToM control is done using SensAble’s C++ software libraries.

This test-bed is presently completed and functional. Possible enhancements or changes include:

1. Adding spool position feedback to all four degrees of freedom.
2. Reducing the size of the computer and electronics and making the test-bed totally stand alone.
3. Replacing the load sensing main pressure regulator with an electronically controlled pressure regulating valve.

4.2 Modeling of HEEnRE

Creating a model of HEEnRE is needed for several reasons. First it provides physical insights into how the system works and how the subsystems interact. It can also be used for controller design and synthesis, model based force estimation, simulation and real-time human in the loop experiments.

4.2.1 Valve

![Diagram of PVE/PVG32 Valve](image)

Figure 2: PVE/PVG32 Valve.

Probably the most important and complex aspect of modeling HEEnRE is the electro-hydraulic valve. The Sauer Danfoss PVG-32 valves are proportional valves designed to be controlled by electronic joysticks for use in mobile hydraulic applications. They are designed to deliver a steady-state flow proportional to the input voltage signal making them ideal for this application. These valves can be stacked and can operate in an open-center configuration with the addition of a load sensing main pressure regulator. This allows this valve assembly to be directly interfaced with a constant displacement gear pump like the one on the 4410 Series tractor. The load-sensing feature means that the valves do not load the tractor when the system is not being used. At the same time the individual closed-center proportional valves hold the actuators in place while the valves are in their neutral position.

The PVG-32 valves have three major components: a main spool, pilot spool controller and a main pressure regulator. The main pressure regulator is essentially a normally open throttle valve that constricts the main flow in order to produce main system pressure, $P_s$, for the individual closed-center valves that
operator each degree of freedom. The pressure regulator tries to maintain $P_s$ above the load sense pressure, $LS$. The load sense pressure is driven by the maximum port pressure that is actively controlling the load. The relationship between $P_s$ and $LS$ can be approximated by the following transfer function.

$$\frac{P_s(s)}{LS(s) + P_{\text{margin}}} = \frac{1}{\tau_{P_s} s + 1} \tag{5}$$

The pressure margin, $P_{\text{margin}}$, is around 1.05 MPa (153 psi) and the time constant, $\tau_{P_s}$, is around 0.012 seconds (12.6 Hz). There is also a dynamic relationship between the port pressures and the load sense pressure. For each degree of freedom

$$LS_i = \begin{cases} P_c & \text{if the } i^{th} \text{ cylinder is extending} \\ P_{\text{min}} \neq 0 & \text{if the } i^{th} \text{ spool is in the dead zone} \\ P_r & \text{if the } i^{th} \text{ cylinder is retracting} \end{cases} \tag{6}$$

Only the largest of the four $LS_i$ signals will drive the load sense pressure and the main system pressure. There is also a dynamic relationship between the max $LS_i$ and $LS$.

$$\frac{LS(s)}{\max\{LS_{i-4}\}(s)} = \frac{1}{\tau_{LS} s + 1} \tag{7}$$

This time constant, $\tau_{LS}$ is equal to 0.018 seconds (8.9 Hz). For a sample of this response see Figure 3. This model was derived empirically, but it is similar to a pressure compensator model derived analytically by Kappi and Ellman [23].

The spool is moved back and forth in order to adjust the orifice size between one port and tank and an equally sized orifice between the other port and the main gallery pressure, $P_s$. When a neutral signal is given to the valves the spool centers itself so that the overlap in the spool prevent any internal leakage. It is this overlap that causes the dead-band in the system. These spools are also designed to open the port pressures to $LS$ right before they move enough to create a control orifice. This is good from an energy savings point of view, but it adds delay to the system. When joysticks are used to control these valves the input signals are slowly changing and the control is open-loop in nature so this is not a problem. However, this delay can cause problems when closed-loop feedback control is used because of the delay and because the dynamics of the system vary so much.

The last major component of the PVG-32 valves is the electronically controlled spool stage. This stage is shown to the left in Figure 2. Four small solenoid valves are arranged in a wheatstone bridge configuration in order to move the main spool back and forth. This wheatstone bridge uses the main system pressure and drains to tank. The valves are modulated using a PWM (pulse width modulated) signal at 40Hz. A
Figure 3: This plot shows the system pressure response to a negative step in boom input voltage. Notice how the LS jumps up to $P_r$ and $P_s$ builds up to a value offset from the LS pressure. The bottom plot compares the measured $P_s$ to the value for $P_s$ calculated from $P_r$ and the dynamic model.

The block diagram of this system is shown in Figure 5. When the main system pressure is above 500-600psi the bandwidth of the spool control stage is around 7-8Hz (Figure 6). If all the main valves are closed or moving through the dead-band region, the system pressure will drop to its minimum pressure around 150-200psi because none of the ports are pressurizing the load-sense pressure line. The spool’s bandwidth reduces to less than 3 Hz when the pressure drops to the minimum pressure level. In turn, this compounds the sandwiched dead-band problem because the slow dynamics between the inverse dead-band and the dead-band become even slower as the spool passes through this critical region. The actual dynamics vary with oil temperature and supply pressure, $P_s$.

The dynamics between the input voltage, $V_{in}$, and the spool position, $X_{sp}$, can be approximated for low frequencies using a second order system with a pure delay element. This delay is likely a result of the 40Hz update rate of the PWM controller. Experimental results from Figure 6 show that the following equation holds for system pressures above around 500-600psi ($V_{X_{sp}} \propto X_{sp}$).
The spool position controls the main flow going to the cylinders by changing the orifice between one port and tank and the other port and supply. These orifices can be described using a standard orifice equation[47]. The relationship between flow, $Q$, and pressure drop across the orifice, $\Delta P$, can be described in general using the following equation.

$$Q = C_d A_0 \sqrt{\frac{2}{\rho} \Delta P} = K_q(x_{sp}, T) \sqrt{\Delta P}$$  

(9)

Where $C_d$ is the discharge coefficient and $A_0$ is the orifice area. The combined term $C_d A_0$ is a function of spool position $X_{sp}$ because the area and shape of the orifice change as the spool moves. As the temperature
increases density $\rho$ will go down and $C_d$ will go up due to a decrease in viscosity of the oil. Both of these will result in more flow for the same pressure drop. The effect of oil temperature will be ignored. For controller simplicity, it will be assumed the relationship between flow will be a function of pressure drop and spool position.

\[
Q_c = \text{sign}(\Delta P_c)K_{q_c}(x_{sp}, T)\sqrt{\left|\Delta P_c\right|} \\
Q_r = \text{sign}(\Delta P_r)K_{q_r}(x_{sp}, T)\sqrt{\left|\Delta P_r\right|}
\]

Valve orifice flow coefficients, $K_{q_c}$ and $K_{q_r}$, control the flow going in and out of the capside and rodside of the cylinder. The pressure drop, $\Delta P$, is measured across the valve orifice from the main system pressure to port or tank to port.
4.2.2 Hydraulics

The compressibility of the hydraulic lines will be modeled between the valve orifices and each side of the cylinder. This will be especially useful for simulation purposes because it is a way to calculate the pressure states of the system. Each volume of fluid will be modeled as a single control volume. The differential equations for capside and rodside pressure will be modeled as follows.

\[
\frac{V_c}{\beta_e} \dot{P}_c = -A_c \dot{x}_{cyl} + Q_c \quad (12)
\]

\[
\frac{V_r}{\beta_e} \dot{P}_r = +A_r \dot{x}_{cyl} + Q_r \quad (13)
\]

The subscripts \(c\) and \(r\) represent the capside and rodside of the hydraulic cylinder. The effective bulk modulus, \(\beta_e\), actually takes into account multiple mechanisms that affect the perceived compressibility of these control volumes: the actual compressibility of the oil, the compressibility of dissolved air in the oil, trapped air in the system and the flexibility (expansion) of the rubber hoses [47]. The volume of oil, \(V\), changes linearly with the displacement of the cylinder with constant of proportionality being the area of the cylinder, \(A\).

4.2.3 Manipulator

Modeling the manipulator will be needed for two different reasons: estimating exogenous forces and creating the virtual excavator simulation. In both cases, a simplified planar model is sufficient. The boom, dipper-stick and bucket degree of freedom all work in a plane. The swing degree of freedom rotates this plane and is not affected by gravity. Modeling the mass and centroid of the last three links is sufficient information to estimate what portion of the joint torque (hydraulic cylinder force) is due to gravity. The mass and centroid will be found using data generated from the system. This will more than likely be done off-line. In order to create the dynamic model for the virtual excavator, inertia will also need to be needed. Inertia from solid modeling of HEnRE done by Frankel [9] will be used as approximations for the real inertia of HEnRE’s links. For consistency, Frankel’s mass and centroid values will also be used in the virtual excavator.

Another major mechanical property that will need to be modeled is friction. The friction in the system is primarily located in the cylinder’s seals and the bushings. A friction term will be estimated for each degree of freedom. Initially this will be done using a viscous-coulomb model [66], but may incorporate more complicated models if they provide a significant improvement[4]. Friction terms will be found using system data and will be used for both force estimation and the virtual excavator.
4.2.4 Kinematics

Kinematic transformations are necessary for simulation and control of HEnRE. Excavators essentially have three different domains that need to be mapped: task-space (cartesian space), joint-space (joint angles) and cylinder space (cylinder lengths). Kinematic relationships exist that can equate the variables in the three coordinate systems. Their energy variables can also be transformed using Jacobian transforms. A standard robotic Jacobian matrix can be used to transform between task space force/velocity and joint space torque/angular velocity. The partial derivatives $\frac{\partial \dot{x}_{cyl}}{\partial \theta}$ can be used to relate each cylinder’s force and velocity to its respective joint space angular velocity and torque. These transforms are programmed in C and implemented as Matlab S-functions that can be used for simulation or control. These functions are maximized for speed by minimizing the number of trigonometric evaluations and algebraic manipulations.

4.3 Velocity controller design

![Proposed closed-loop position controller](image)

Ideally it would be possible to directly control the velocity of each cylinder. Similar to many other proportional directional control valves, the input to the valves used in this system actually corresponds to a steady-state spool position. An internal feedback loop controls the spool position using a PWM regulated solenoid valve bridge (Figure 5). Spool position feedback is supplied from a LVDT (Linear Variable Differential Transformer). Currently, this signal is only available on one of the PVE electronic spool control modules. In turn, the spool position determines an orifice size that controls the flow between each port and either tank or the pressurized main gallery. The general block diagram of the proposed controller is shown in Figure 7. This control has several important features including:

1. A feedforward term, $v_d = \dot{x}_d$, is used to minimize the control effort generated by the feedback error signal. This term essentially supplies the nominal cylinder velocity need to follow the desired trajectory.
2. PD control to reject position and velocity error.
3. Look-up table to find the desired spool position command ($V_{in}$) that will produce the flow corresponding to the desired corrected cylinder velocity ($v_{dc} = v_d + k_d \dot{e} + k_p e$).
Finding the desired spool position \((V_{in})\) requires knowing the desired flow as well as the pressure drop across the port being controlled. This is represented by the \(\Delta P\) input into the look-up table. Similarly, main system pressure, \(P_s\), is an input into the spool dynamics block \((G_{sp}(s))\) because \(P_s\) affects the response of this controller.

Spool dead-band will limit the ability of a system to track an input profile. However, if the controller is designed correctly it will always track as well as possible and will maintain system stability when crossing through the dead-band. It is also desirable that the controller is robust to a variety of uncertainties including: oil temperature, orifice modeling error, spool dynamics, pressure regulator dynamics and the mass/inertia of the manipulator. A particular area of concern is the main pressure regulator and the effect that it has on the closed-loop control system. If these dynamics cannot be overcome, the load-sensing main pressure regulator will need to be replaced with an electronically controlled pressure regulator. This controller will actually be implemented as a multi-rate system because the spool position control loop (Figure 5) has a fixed 40Hz update rate and the outer cylinder velocity control loop (Figure 7) will run at 1000Hz. The need for velocity signals will be solved by using the PHANTOM’s built in estimated velocity signal and by filtering the cylinder’s position signals.

4.4 Force Estimation

The exogenous forces acting on the end effector is necessary for force reflecting teleoperation. Rather than directly measure the force exerted by an excavator’s end effector, it is more practical to indirectly estimate this force from joint torques \([46, 64]\). Mounting a sensor directly onto the bucket would be difficult and prone to damage. One method is to use load pins to measure the forces between the cylinders and the excavator links. A more economical solution is to use pressure sensors mounted on each side of the cylinder. The disadvantage is that this measurement includes the internal friction of the cylinder seals \([67]\). The same pressure sensors can also be used for valve control. The hydraulic force \(F_{hydr}\) is the actual hydraulic force acting on the cylinder’s rodside and capside areas.

\[
F_{hydr} = A_cP_c - A_rP_r = F_{inertia} + F_{external} + F_{friction} + F_{gravity}
\]

The hydraulic force is also equal to the sum of the other forces acting on the system: forces from internal friction, forces due to gravity, forces from accelerating the manipulator’s inertia and external forces acting on the bucket. The estimator will attempt to cancel out gravity and friction terms leaving only external and inertial forces. The last of these force components, external bucket force, is the only one that is wanted for
force reflecting teleoperation. Removing the inertial forces would be ideal, but would require a full dynamic model solved in real-time. These forces are negligible compared to friction and gravity terms and can be ignored [66]. By using a viscous-coulomb model and removing the gravity terms, it is possible to obtain a satisfactory estimation of the exogenous force from the pressure readings[67]. Another technique has been proposed that uses cylinder pressure in the friction estimate[4]. The advantage of this method is that it takes into account how pressure in the cylinders affect the friction in the seals. As cylinder pressure increases so does the friction in the seals. This method was developed using constant velocity set points and was designed for use in a simulation, rather than real-time force estimation.

Force estimation will not be used in the cylinder velocity controller discussed in the previous section. This controller does have force compensation, but it is implemented directly using line pressure measurements in its control law. Instead this force estimation will be used to adapt a higher level haptic network that links the force-reflecting haptic interface to the robotic backhoe.

4.5 Force Reflecting Architectures

Two different force-reflecting architectures will be implemented on HEnRE and the virtual excavator: position mode and rate mode with a force modulated spring. In position mode the motion of the slave is an amplified version of the human’s hand and the force displayed to the human is a scaled down version of the external forces acting on the excavator’s bucket. This can be seen by looking at an “idealized” two-port network of the system in Figure 15.

\[
\begin{bmatrix}
  F_h \\
  -V_e
\end{bmatrix} =
\begin{bmatrix}
  0 & S_{force} \\
  -S_{velocity} & 0
\end{bmatrix}
\begin{bmatrix}
  V_h \\
  F_e
\end{bmatrix}
\] (15)

In this application the force scale is less than one, \( S_{force} < 1 \), and the velocity scale (or spatial scaling) greater than one, \( S_{velocity} > 1 \). Rate mode will be implemented similar to the scheme proposed by Parker et al. [51]. In this technique the spring stiffness of the joystick is modulated to reflect the forces acting on the
end effector (Figure 16). The displacement of the master joystick $X_h$ is proportional to the velocity of the slave. The exogenous force acting on the bucket is reflected by modulating the joystick’s stiffness, $K_c(f_e)$ (Figure 17). This stiffness function is bounded from above and below to limit the stiffness and assure that $K_c(F_e)$ remains positive.

\[
\begin{bmatrix}
F_h \\
V_e
\end{bmatrix} =
\begin{bmatrix}
K_c(F_e)X_h \\
S_{velocity}X_h
\end{bmatrix} =
\begin{bmatrix}
K_c(F_e)\frac{V_h}{\beta} \\
S_{velocity}\frac{V_h}{\beta}
\end{bmatrix}
\]

(16)

\[
K_c(f_e) = K_{nom} + K_r * F_e
\]

(17)

Haptic feedback can also be generated using virtual fixtures [53]. Using virtual fixtures to aid in operator control of hydraulic machinery has been demonstrated by Kontz [26] using a hydraulically actuated lifter. Using a haptic human-machine-interface enables the use of virtual fixtures, but this topic will not be explored by this research.

### 4.6 Passive Energy Balance Monitoring

![Figure 9: Teleoperator with Passivity Controller.](image)

Using time-domain passivity/passive energy monitoring is motivated by the fact that teleoperators are nonlinear and human dynamics are complicated [15]. This is especially true of teleoperators based on hydraulic systems actuated by proportional directional control valves. Passivity is a concept that has been utilized by haptic researchers to deal with this problem. However, many passive haptic systems are overly conservative due to fixed damping designed around a worst case scenario (i.e. contact with stiff environments). Many of the passive controller designs are also model based.

Instead of creating a control that guarantees passivity, the method of time domain passivity enforces passivity by monitoring energy flowing in and out of the system. It then dissipates energy when the system becomes active or produces energy. In actuality, energy is not just dissipated, but the energy output is also limited by decreasing system output in the active port(s). An additional advantage is that it does not require
a model of the system.

This is demonstrated in Figure 9. During passive operation $\beta_1$ and $\beta_2$ are set to zero. If the system becomes active the damping-like terms $\beta_1$ and $\beta_2$ are increased in order to enforce passivity. Time-domain passivity has been applied to a variety of haptics applications: teleoperators [57], haptic interfaces linked to virtual environments [15, 54], virtual, flexible slave robot [55] and general control systems [56]. This has led to several practical issues being addressed and/or brought up in the literature. One issue is noise due to velocity estimation. Normally, velocity is not measured directly, but is estimated from position measurements. This can cause chatter in the passivity controller at low speed when the noise dominates the signal [15]. A practical solution is to use a threshold value that essentially turns off the passivity controller when speeds are too low [24]. In this research the exogenous force will also be estimated.

Resetting the energy in the passivity observer can also improve performance. If energy builds up in the observer when the system is dissipating energy, the passivity controller will not be turned on as fast when the system becomes active [24]. Another observation is that it is not always desirable to dissipate “non-passive” energy in the next time step. In the case of the PHANToM haptic interface it is possible to excite high frequency structural modes, if the passivity controller supplies an impulsive force to the system [54]. This problem can be solved by dissipating the same energy over multiple time steps.

Another practical question is where to put the passivity controller. In the case of HEnRE it will need to be placed outside of the low-level force control loops on the PHANToM and cylinder-space velocity control loop on the backhoe. This way the passivity controller can individually stabilize each valve-cylinder combination. This will require the energy variables to be mapped from Cartesian space to cylinder space. Another question is how to deal with mechanical dissipation in the force measurement [57]. In the case of HEnRE, there is significant friction in the cylinders and the joints. The actual force measurement, $A_r P_c - A_r P_r$, includes these dissipation forces. The most conservative approach would be to have the passivity observer use this force. At the other end of the spectrum is the estimated tip force described in Section 4.4 which attempts to remove the dissipative friction forces. This might result in over estimating the dissipation. Ideally there would be some friction compensation that always underestimated the dissipation, but was not as conservative as having no compensation.

System delay is also a potentially destabilizing element in the system. This delay could be caused by the slow update rate of the PWM spool controller, dead-band in the spool or the main pressure regulator. However, experiments done on a virtual environment indicate that time domain passivity can make a system robust to delay in the system. In Hannaford and Ryu [15], a stable virtual environment’s update rate is reduced from 1000Hz to 66.7Hz resulting in unstable behavior. Stability was maintained with the addition of adding passivity control to the system.
4.7 Virtual HEnRE Simulator

The purpose of creating a virtual HEnRE (V-HEnRE) simulator is for human factors testing. This offers several advantages over doing human factors testing on the real hardware. Benefits of using a virtual excavator include: operator safety, the ability to change system parameters (dead-band, bandwidth, etc) and the ability to instantaneously bury objects in the workspace for the human subjects to find and interact. The purpose of this simulator is not to replace the actual hardware, but rather to enhance testing that is done on the real equipment. Its purpose will be solely for human-in-the-loop testing. All the control algorithms described in this proposal will be tested on the real hardware. The form and function of this simulator will be similar to the virtual excavator created by DiMaio et al. [7].

V-HEnRE will be comprised of several distinct features:

1. Simulation of the hydro-mechanical aspects of HEnRE
2. Simulation of HEnRE’s control system
3. Simulation of soil and buried objects
4. The PHANToM haptic interface for operator interaction
5. A graphical display of HEnRE and the soil model for visual feedback

The hydro-mechanical, control system and environment model will also be simulated in real-time using Matlab’s xPC-target. This combined simulation will communicate with another PC running the PHANToM using UDP socket communication. The control system running the PHANToM will be identical to the one used to operate the actual machinery. The operator will be supplied with visual feedback from a graphical interface. For simplicity the swing degree of freedom will be removed from this simulation. This will turn it into a planar problem. However, this should not significantly reduce the ability to test how the human subjects react to buried objects because most of the motion and forces associated with digging occurs in this plane.

One aspect of this simulator which has not been discussed is the soil model. The soil model used in this simulator will build on the soil model used by the virtual excavator created by DiMaio et al. [7]. Other researchers, have also explored real-time soil models for construction automation [43, 45]. Primarily these models focus on estimating soil properties to aid in calculating optimal autonomous digging trajectories. Objects that mimic buried pipes or cable will also be added to V-HEnRE’s soil model.
4.8 Human-in-the-Loop Experiments

The primary goal of doing human-in-the-loop experiments will be to determine how valve characteristics like dead-band and bandwidth affect operator performance. The primary test will be how well the combined human backhoe system can react to buried objects. Being that human subjects will be involved in these tests, it will be necessary to receive approval from the the Institute Review Board. Test subjects will be evaluated by measuring:

1. How well an object can be detected by the human?
2. How well the combined human-machine system reacts to and limits damage to the buried object?
3. How well the backhoe tracks a desired trajectory during maneuvers.

These tests will be conducted using both rate and position control modes. Each operator will be required to dig a series of virtual trenches. The bandwidth and dead-band will be varied throughout the tests. Buried objects representing buried power lines or utility pipes will be randomly placed in the virtual environment where the test subject is digging.

Data from these tests will be collected and analyzed statistically. The goal will be to determine at what point increasing bandwidth or decreasing dead-band will not significantly improve human performance. This is a practical and economical question because these features affect the cost of the valve. In order to validate the results from this study, the results will be compared with a few tests point taken on the actual excavator.

5 PRELIMINARY RESULTS

The first milestone in this project was completing the HEnRE test-bed in the spring of 2004. Joe Frankel (M.S. 2004) and J.D. Huggins (research engineer) also played a key role in this effort. At this time, HEnRE was interfaced with a PHANToM haptic interface and basic functionality was demonstrated. It can be seen from the plots in Figure 10, that HEnRE is following the motion of the PHANToM interface. Unfortunately, the tracking is poor and the motion is jerky. The jerky motion is due to complex interactions between the human, the controller and the electro-hydraulic valves. The poor tracking is due to the low control gains required to not excite the jerky motion. This data also represents the first attempt to eliminate this problem. Originally, each spool had an additional pressure compensator that tried to make the relationship between input and output linear. These are designed to maintain a linear relationship between the valve input and steady-state flow. This is good for open-loop control signals from a joystick, but it adds additional complexity and dynamics that can destabilize a close-loop controller.

Since the completion of the test-bed, the major thrust of this project has been to model these valves and
design a suitable controller. The results of this modeling effort is summarized in Section 4.2.1. This modeling has resulted in insight into how these valves work. The goal of this controller is to control the speed of the cylinder so the trajectory generated from the human-machine-interface can be tracked. The basic design of this controller is described in Section 4.3. This controller can be broken into two parts: the desired speed control law and the spool position controller that delivers the desired flow. The desired speed control law has a feedforward and a feedback term that is designed to create a velocity input making the cylinder track the desired position and velocity profile. The more complicated part is how to create the desired hydraulic flow.
Figure 11: HEEnRE tracking a sinusoidal input. Notice the poor tracking and jerky motion. This is results of the dynamic interaction between the closed-loop control system, main pressure compensator and the human operator. This data was taken after the individual pressure compensator were removed from the individual PVG32 blocks.

The goal of the spool controller is to specify the spool position that will deliver the desired flow. One way to do this is to make a look up function that relates the valve’s orifice coefficient to spool position. This was implemented on the boom degree-of-freedom as shown in Figure 11. This test did show promise, but it also revealed a new challenge associated with the load-sensing pressure compensator. While the boom is lowering, the trajectory tracking is good and the motion is smooth. However, lifting the boom result in large error and significant feedback effort.

Comments:

- Pressure never builds up as the boom is lowering.
- The look-up table was calibrated at low pressure, so the majority of the desire flow is generated from
the feedforward signal, \( U_f \). This means that position error and the feedback generated input, \( U_p \), does not build up.

- The system pressure is high while the boom is raising in order to overcome gravity.
- The large feedback input, \( U_p \), that is generated while the boom is raising suggests that the commanded velocity (flow) is much larger than the actual flow delivered to the cylinder. This suggests the presence of a significant leakage flow.

By analyzing the data from this test, it was determined that there is a large leakage flow which is dependent on port pressure. This explains the poor tracking while the boom is being raised since the port pressure is high. The explanation for this leakage flow is the load-sensing pressure regulator. The load-sense line connects the port with the highest pressure to a cavity in the main pressure regulator in order to maintain the supply pressure above this port pressure. There is an orifice in this cavity that drains to tank. The purpose of this orifice is to release pressure once a lower port pressure is driving the load-sense or all the spools are in their dead-band range and are therefore closed off from the load-sense line. Notice how the \( LS \) pressure drops at 3.25 seconds as the valve moves through the dead-zone.

Another controller was developed that took this leakage flow into account. Based on the data shown in Figure 11, the leakage flow was solved as a function of port pressure. The measured velocity from Figure 11 is compared with the calculated velocity from the original model and the new model with leakage in Figure 13. The valve orifice coefficient was resolved in order to eliminate the low-pressure leakage that was embedded in the look-up table used by the previous controller. Basically, the new controller took the desired flow calculated from the desired velocity control law and added the leakage flow to it. This total flow represents the sum of the leakage flow and the flow necessary to move the cylinder at the desired speed. Results from this controller are shown in Figure 13. This resulted in better overall tracking. However, it did cause the
system to oscillate.

The controller without the leakage compensating term was also tested with a PHANToM Omni haptic interface. Results from this test are shown in Figure 14. Notice the good tracking/low haptic force while the boom is lowering. Similar to the plots with the sinusoidal input there is poor tracking and high position error while the boom is raising due to the leakage. There is also some oscillation between the hydraulics and human operator in the haptic force signal while the boom is raising. This is caused by adding the additional dynamic loop between the human operator and the haptic interface.

The fact that all of these controllers are on the verge of oscillatory behavior and have poor tracking is an acute area of concern since this research is proposing additional levels of control in the form of position and force-based haptic feedback loops. Multi-degree-of-freedoms tests add additional complexity since four...
Figure 14: HEnRE tracking the PHANToM’s input with the same valve controller used in Figure 11. Notice the good tracking/low haptic force while the boom is lowering. Similar to using the sinusoidal input there is poor tracking and high position error while the boom is raising due to the leakage. Also note that start of an oscillation between the hydraulics and human operator while the boom is raising.

different valves and valve inputs are affecting the load-sensing pressure regulator. The load-sensing pressure regulator makes it difficult to design a controller that can track a desired trajectory and has smooth, stable behavior. It also makes a stability proof difficult, if not impossible. Probably the best solution to this problem is to replace the load-sensing element of this valve assembly. The pressure regulator is essentially a pressure control valve. Currently, the pressure set point is set by the load-sensing element. A more appropriate design for closed-loop control replaces this regulator with an electro-proportional pressure regulating valve.

Removing and replacing the load-sensing pressure regulator would have the following benefits.

- Improve responsiveness of the individual flow valves by maintaining system pressure even when the spools pass through the dead-zone regions.
• Eliminate the nonlinear dynamic relationships between port pressure and the main system pressure.
• Remove the leakage through the load-sense pressure port.
• Eliminate nonlinear coupling between the individual proportional directional control valves.
• Give a flexible and controllable way of setting the main system pressure

6 CONTRIBUTIONS

The goal of this research is to explore the application of haptic control to hydraulic machinery. An important element in this system is the hydraulic valves since they can limit the bandwidth of the system and in the case of proportional directional valves introduce dead-band due to the spool design. This research aims to develop and create control laws and estimation techniques that enable haptic technology to be applied to cost-effective hydraulic machinery and evaluate what role valve characteristic like bandwidth and dead-band play in limiting operator performance.

The expected contributions of this research are as follows:

1. Implement a low-level nonlinear velocity controller that is robust to system uncertainty.
2. Evaluate the limitations of human performance imposed by valve bandwidth and dead-band.
3. Analyze the role that the load-sensing pressure compensator has on closed-loop control of hydraulic system.
4. Extend time-domain passivity/passivity monitor architecture to highly nonlinear, hydraulically systems.
   • Explore how to best deal with mechanical dissipation in the time-domain passivity/passivity monitoring scheme in a non-conservative and robust fashion.
   • Implement time-domain passivity/passivity monitoring in a real teleoperator with significant delay due to dead-band and slow update rates.
   • Implement a time-domain passivity/passivity monitoring system on a teleoperator using a rate controlled force reflecting haptic interface.

This project can be broken up into three different stages: constructing of the HEnRE test-bed, developing, implementing and testing the control algorithms on HEnRE and exploring the effect of dead-band and spool bandwidth on human performance. With the exception of a few additional modifications, the construction of the test-bed has been completed. Currently the project is in the control system development stage. A lot of this effort has focused on modeling and control of the valves. This is a particularly important stage because
it will affect how well the proposed higher-level haptic control strategies will work. Once the necessary valve controller and/or valve modification are made the second part of this stage will be to implement and test the higher-level haptic control algorithms. The goals of the higher level control algorithms will be to reflect forces from the end effector while maintaining system stability at all times. Human-in-the-loop testing will be the final stage. These tests will be designed to evaluate the effective of these control strategies and explore how various characteristics of the hydraulic system limit operator performance.

Tentative time table for the remainder of the proposed research:

2. Fall 2005: Complete the implementation of force-reflecting architectures on HEnRE and complete the V-HEnRE simulator to be used for human-in-the-loop testing.
References


