Hydraulic Manipulator Design, Analysis, and Control at Oak Ridge National Laboratory

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HYDRAULIC MANIPULATOR DESIGN, ANALYSIS, AND CONTROL AT OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

In the early developmental stages of robotics, hydraulics played an important role. Many of the early high-payload capacity manipulators were actuated by hydraulic cylinders and hydraulic rotary actuators. As the power-to-weight ratio of electric motors increased, they eventually came to be the preferred form of actuation for robotic manipulators because of the relative ease of operation, control, maintenance, and for general cleanliness. Recently, however, task requirements have dictated that manipulator payload capacity increase to accommodate greater payloads, greater manipulator length, and larger environmental-interaction forces. General tasks such as waste storage tank clean-up and facility dismantlement and decommissioning require manipulator lift capacities in the range of hundreds of pounds rather than tens of pounds. To meet the increased payload capacities demanded by present-day tasks, manipulator designers have turned once again to hydraulics as a means of actuation. Hydraulics have always been the actuator of choice when designing heavy-lift construction and mining equipment such as bulldozers, backhoes, and tunneling devices. In order to successfully design, build, and deploy a new hydraulic manipulator (or subsystem) sophisticated modeling, analysis, and control experiments are usually needed. To support the development and deployment of new hydraulic manipulators Oak Ridge National Laboratory (ORNL) has outfitted a significant experimental laboratory and has developed the software capability for research into hydraulic manipulators, hydraulic actuators, hydraulic systems, modeling of hydraulic systems, and hydraulic controls. The hydraulics laboratory at ORNL has three different manipulators. First is a 6-Degree-Of-Freedom (6-DoF), multi-planar, teleoperated, flexible controls test bed used for controls and teleoperator research. Second is a 2-DoF Flexible/Prismatic test bed used for the development of waste tank clean-up manipulator controls, thermal studies, system characterization, and manipulator tracking. Finally, is a human amplifier test bed used for the development of an entire new class of teleoperated systems. To compliment the hardware in the hydraulics laboratory, ORNL has developed a hydraulics simulation capability including a custom package to model the hydraulic systems and manipulators for performance studies and for controls development. This paper outlines the history of hydraulic manipulator developments at ORNL, describes the hydraulics laboratory, discusses the use of the equipment within the laboratory, and presents some of the initial results from experiments and modeling associated with these hydraulic manipulators. Included are some of the results from the development of the human amplifier/de-amplifier concepts, the characterization of the thermal sensitivity of hydraulic systems, and end-point tracking accuracy studies. Experimental and analytical results are included.
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1. INTRODUCTION

1.1 GENERAL COMMENTS ON HYDRAULICS

Hydraulically actuated manipulators play an important role in real applications because of their high payload-to-mass ratios compared with conventional electrically actuated manipulators. Comparable power-to-mass ratios range from 3.3 kW/kg (2 hp/lbm) for hydraulic systems to 50 W/kg (0.03 hp/lbm) for electric systems.\(^1\) The best electric motors are now getting as high as 1 kW/kg (0.6 hp/lbm) power-to-mass ratios.

In many industrial applications where a high power capacity is desired, hydraulics is the general form of actuation. Hydraulics provides a number of unique features. First, the fluid provides a natural method of lubrication and cooling. There is no phenomenon in hydraulic components that is equivalent to the saturation and concomitant losses in magnetic materials as is associated with electric motors. Torque output from a hydraulic machine is limited only by safe stress levels. Furthermore, hydraulic actuators have a high stiffness compared to other drive devices. In addition, they have a higher speed of response as well as large torque-to-inertia ratios, providing high acceleration capacity. Hydraulic components may be operated in continuous, intermittent, reversing, and stalled conditions without damage. In addition, rotary and linear hydraulic actuators are available for many different sizes and power ranges.\(^2\)

Hydraulics technology is not without its disadvantages. For example, hydraulic power is not as readily available in most industrial settings as is electric power and most stationary applications must have a hydraulic power supply installed. Hydraulic components are expensive. Hydraulic fluids are sometimes flammable and/or considered to be hazardous waste. Hydraulic systems almost always leak and are therefore considered messy. Hydraulic fluids must be filtered and in some cases filtered thoroughly for high-performance applications such as servovalves. Contaminated oil is one of the primary reasons for component failure in hydraulic systems. Hydraulic actuators are not generally as flexible and easy to use for low-power applications as are electric actuators.

1.2 HISTORY OF HYDRAULIC MANIPULATORS AT OAK RIDGE NATIONAL LABORATORY

The applied nature of the projects at Oak Ridge National Laboratory (ORNL) and the direct results of the value of hydraulics has made it the power source of choice in many ORNL projects. Consequently, ORNL has had considerable experience with hydraulic manipulators and movable systems over the past decade. This section briefly describes some of the hydraulic hardware systems developed at ORNL.

Except for some very early work with commercially available teleoperated manipulators, one of the first hydraulic systems developed at ORNL was the Soldier Robot Interface Platform (SRIF) vehicle shown in Fig. 1.\(^3\)
The SRIP vehicle was designed and built with the assistance of the Tooele Army Depot in Utah. The SRIP has a hydrostatic-drive transmission and was fitted with an electric arm and numerous sensor systems. It was designed for two purposes: the military intended it as a platform for research into unexploded ordnance disposal, and the Department of Energy (DOE) supported it for buried waste site characterization and remediation. One of the particularly challenging aspects of the SRIP development was providing it with the ability to maintain an accurate trajectory necessary for complete coverage of an area during a waste characterization survey in spite of limited accuracy wheel position sensors, a natural tendency to slip on rough terrain and/or loose soil conditions, and a hydrostatic transmission. At the time of the development of SRIP, low-cost and accurate Global Positioning System (GPS) sensors were not readily available.

Another hydraulic system developed at ORNL was the Future Armor Rearm System (FARS), shown in Fig. 2. The FARS was designed and built with the assistance of Tooele Army Depot. The FARS was developed to allow the Army to rearm its new M1A1 tanks without exposing the soldier to the hazards of the battlefield. The FARS hydraulically actuated arm served several purposes: (1) to dock with the empty tank; (2) to be a communication link between the tank and the FARS rearm vehicle; and (3) to transfer the ammunition between the tank and the FARS vehicle. Control of the FARS arm proved to be a challenge in achieving the fine motion required to dock with the tank rearm port. Management of the interaction forces between the arm and the docking port during contact was proven to be a hydraulic system challenge. Ultimately, interaction forces were controlled by developing a compliant rearm port on the tank. Flexibility and low natural frequency would be a problem with the FARS arm if it were moved quickly. To avoid exciting the arm's structural dynamics, however, the joints are moved slowly.
The next system developed by ORNL was the Telerobotic Small Emplacement Excavator (TSEE), shown in Fig. 3. Like the SRIP, this system was developed as a dual-use system. The military supported development as a platform for research into unexploded ordinance disposal, and DOE wanted it for buried waste site characterization and remediation. One of the particularly challenging aspects of the TSEE development was providing it with the ability to be remotely operated as well as be operated as it was originally designed with no interference to the operator from the modifications for remote operation. In addition, the TSEE control panel was made to be portable with an intuitive operator interface. Arm and bucket motions were controlled by a single joystick where the direction of the joystick motion matched the physical direction and motion of the arm and bucket. The control system provided an adjustable dig floor to prevent the operator from inadvertently digging below a desired level. These intuitive features made the TSEE easy and simple to use; in fact, over half of the soldiers surveyed in an operational experiment comparing the use of the remotely operated TSEE with a conventionally operated version preferred the remotely operated TSEE. Low-cost and reliable proportional valves were used in the TSEE vehicle. The TSEE has also been operated over a computer internet link over distances of thousands of miles.

As part of the DOE Robotics Technology Development Program's support of decontamination and dismantlement (D&D) efforts, the Dual-Arm Work Module (DAWM) was developed by ORNL and RedZone robotics. This system is the most current manipulator in the evolutionary development of telerobotic manipulators at ORNL. The DAWM, shown in Fig. 4, features two 6-Degree-Of-Freedom (D.O.F.), hydraulically actuated, Schilling manipulators, and a 5-D.O.F., hydraulically actuated base. It was initially deployed off a 4-D.O.F. electrically actuated, gantry-like transporter and suspended from an overhead crane but could also be deployed off of a mobile platform. Each of the Schilling arms is capable of lifting 240 lb fully extended. A similar system will be used to support the D&D activities at the CP-5 reactor at Argonne National Laboratory (ANL). The ORNL DAWM is used for support of the D&D effort at ANL in the areas of operator training, tool and fixture testing and development, control algorithm development and testing, cost/benefit experimental analysis, and operator interface design and evaluation. The DAWM is shown in a D&D mockup in Fig. 5.

Another hydraulic manipulator system at ORNL is the Schilling 7F, 6-D.O.F., multiplaner, teleoperated, flexible controls test bed used for controls and teleoperator research for hydraulically actuated, flexible-link manipulators. This system is shown in Fig. 6.
Fig. 3. The Telerobotic Small Emplacement Excavator (TSEE).

Fig. 4. The Dual-Arm Work Module (DAWM).
This system is presently being used for event-based controller integration in support of ORNL's Gunite And Associated Tanks (GAAT) clean up effort. This system has also been used for mock-up of larger arms and for preliminary demonstrations of hardware that is normally deployed off of larger manipulators. This system is normally teleoperated, but it has been converted to run robotically. Limited accuracy and low reliability remain a problem.
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2. HYDRAULIC SYSTEM MODELING

2.1 GENERAL HYDRAULIC MODELING AND ANALYSIS

When considering the transfer function from voltage input to speed output electric motors respond as a simple lag device. In contrast, hydraulic actuator transfer functions between voltage and speed are basically quadratic in form with a relatively high natural frequency. This difference makes controller design and analysis much more difficult for hydraulic systems.

The flexible/prismatic test stand, shown in Fig. 7, was developed as a research manipulator for the ORNL Hydraulics Laboratory.

![Flexible/prismatic test stand in the ORNL Hydraulics Laboratory.](image)

Fig. 7. The flexible/prismatic test stand in the ORNL Hydraulics Laboratory.

Its main objective is to serve as a research test bed for studying the effects of hydraulics and link flexibility on manipulator design and control. The goal of the design is to have a realistically sized actuator and payload. The mechanical details are described in greater detail in the Sect. 3, Experimental Results.

Consider two representations of the valve command (volts) to position output (in.) transfer function, \( G \), for a typical hydraulic actuator shown in Eqs. 2.1a and 2.1b:

\[
G_1(s) = \frac{437,6352}{s(s+37.53)}, \quad (2.1a)
\]

\[
G_2(s) = \frac{35782}{s(s^2 + 81.7618s + 2606.1)}, \quad (2.1b)
\]

where \( s \) is the LaPlace transform variable.
These transfer functions are taken from actual fits to data obtained by using varying frequency sine waves as inputs to the prismatic joint servovalve of the ORNL flexible/prismatic test bed at the nominal operating temperature of ~25°C. Analytically derived transfer function representations from the valve command to the position output are presented in Merritt's book.² For a prismatic actuator with valve command in in., and the position output in in., one obtains:

\[
y = \frac{K_{q_0}x_v}{A} s^2 + \left( \frac{K_{PTM}M}{4\beta_e A^2} + \frac{B_pV_T}{4\beta_e A^2} \right) s + \left( 1 + \frac{B_pK_{PTM}}{A^2} \right)
\]  

(2.2a)

Note that all of the symbols for all of the equations in this report are defined in Appendix A. For reference, the transfer function for the valve command in inches and the output position in radians for a rotary actuator is given as

\[
\theta_m = \frac{K_{q_0}x_v}{D_m} s^2 + \left( \frac{K_{PTm}I_T}{4\beta_e D_m^2} + \frac{B_mV_T}{4\beta_e D_m^2} \right) s + \left( 1 + \frac{B_mK_{PTm}}{D_m^2} \right)
\]  

(2.2b)

Appendix B contains the governing equations for the derivation of the transfer functions of Eqs. 2.2a and 2.2b.

Examining Eqs. 2.1a and 2.1b in light of Eq. 2.2a, one can determine that the third-order transfer function of Eq. 2.1b is the one that is physically correct (second-order voltage to speed with an integrator); however, the second-order transfer function of Eq. 2.1a is the analytically equivalent electrical motor model for the hydraulic actuator. Equation 2.1a was obtained by fitting the nonphysical second-order transfer function to the same set of data used for the fit of Eq. 2.1b. A similar model can be obtained by developing a reduced-order transfer function from Eq. 2.1b. Note that the third-order fit has 50 times less error than the second-order fit. Bode plots from both models are shown in Fig. 8.

Notice that there is little difference between the frequency response of either representation except at the high frequencies; however, the phase angle plots are much different at frequencies greater than 10 rad/sec, as is expected because of the difference between the third-order vs the second-order transfer functions (second-order system with no constant term will go from -90° to -180°, whereas the third-order system phase will go from -90° to -270°). It is precisely this difference in the dynamic performance that makes hydraulic systems more difficult to control.

Consider the root loci of Fig. 9. These correspond to the transfer functions of Eqs. 2.1a and 2.1b and are for a proportional controller only.
As the gain is increased in the root locus plot for the second-order transfer function, $G_1(s)$, the roots move from one on the negative real axis and one at the origin to both at the same point on the negative real axis and then along a line parallel to the Y-axis. However, at no time do the roots ever move into the right-half plane, indicating that (at least theoretically) this system remains stable for all values of the proportional gain. (Certainly, this is not true in reality since, as when the gain is increased, the system is no longer linear, and the transfer function does not adequately describe the system dynamics. In addition, noise becomes an important factor as the gain increases.) Considering the root locus for the third-order transfer function, $G_2(s)$, one observes that as the value of the proportional gain is increased, the real parts of the two complex conjugate roots move into the right-half plane. This indicates that there are values of the gain where the system becomes unstable regardless of nonlinearities and/or noise. This added complexity makes the development of controllers for hydraulically actuated manipulators more difficult than for electrically actuated manipulators and requires more extensive and more detailed modeling and analysis prior to hardware implementation. In addition, important hardware choices must be made in the initial design if a high-performance system is to be achieved. This includes the use of stiff hydraulic lines (e.g., metal as far as possible), the mounting of servovalves as close as possible to actuators, careful attention to the
50 -

-50-

-80

1

1

1

1

£

1

1

1

1

1

1

1

Real Axis •

-80 -60 -40 -20 0 20 40 60 80

Fig. 9. Root loci plot for transfer function models of Eqs. 2.1a and 2.1b with a proportional controller. The top figure is for $G_1(s)$ and the bottom for $G_2(s)$.

removal of all entrapped air, and selection of high-performance components, including low-friction actuators and zero deadband valves. Because of the need for detailed modeling and analysis, the following sections describe models developed for some of the ORNL hydraulic systems that are used for controller design and evaluation.

2.2 FLEXIBLE/PRISMATIC TEST STAND DESIGN AND MODELING

Models were developed for the flexible/prismatic test bed mechanical design as well as for the hydraulic systems. Mechanical modeling was used in the test bed design and is discussed in Section 3.2.1. The hydraulic system of the flexible/prismatic test bed was modeled in detail using Simulink and Matlab. It was necessary to use a computer modeling package as opposed to relying completely on analytical models because of the significant set of nonlinear behaviors present in typical hydraulic systems. These nonlinearities include nonlinear friction, both stiction and Coulomb friction; nonlinear drive-train compliance; actuator saturation; mechanical backlash and deadband; servovalve nonlinear friction and deadband; entrapped air within the hydraulic fluid; nonlinear servovalve orifice effect; the effects of fluid contamination; pressure losses in piping, including bends and reductions; asymmetric actuator
areas and time-varying nonlinear effects. Not all of these nonlinearities were modeled, but several of the important ones were included in the formulation of the governing dynamics' equations. These equations are shown in Appendix B. An example of the Simulink model of the flexible/prismatic test bed is shown in Fig. 10.

![Simulink model diagram](image)

**Fig. 10.** Flexible/prismatic test bed hydraulic system model in Simulink.

### 2.3 HUMAN EXTENDER/AMPLIFIER MODELING AND ANALYSIS

#### 2.3.1 Description of Human Extender/Amplifier

A human extender (also called a human amplifier system) is a device that amplifies the lifting capacity of a person and allows a preselected amount of force feedback to the operator (e.g., the operator can feel any desired portion of the load). This type of manipulator system is similar to a teleoperated system in that a human operator is coupled directly to the mechanical system; however, it is fundamentally different from the traditional teleoperated manipulator system in the sense that the master and slave manipulators are one integral unit. Applications of a human extender system include the following:

1. Material handler in an unstructured environment where manipulating and orienting large objects, while transmitting back to the operator a fraction of the object’s dynamics (i.e., its weight, contact forces, slippage, etc.), could significantly enhance productivity, quality, and safety (e.g., missile loader and rearming tanks/heavy artillery for the military).
2. Rescue operations (e.g., Oklahoma bombing rescue, firefighting).
3. Material handler in the construction industry (i.e., taking large loads off trailers, as is typically done by a large crane; moving large pipes; putting up sheetrock; etc.).
4. Medical (e.g., patient manipulation).
5. Material handler in the mining industry.
6. Material handler in the forestry industry.

The human extender problem was first addressed in the 1960s by General Electric during the Hardyman project. More recently, H. Kazerooni has been working on a scaled-down version of a similar concept. These systems have always had difficulties because of profound stability issues associated with varying dynamics and gross nonlinearities in the fluid power system (e.g., nonlinear pressure-flow relationship, time-varying fluid properties, large quantities of nonlinear friction, and time-varying system dynamics).

The goals of the ORNL human amplifier system are to achieve high lift capacity (around 500 lb), force amplification (from 1 to 500), and tracking performances (submillimeter range). The effects of human dynamics must be minimized to achieve these goals.

Detailed hydraulic models that include most of the nonlinear fluid and mechanical dynamics have been generated for a 1-D.O.F. human extender test stand. Fundamental stability limits and how they relate to the mechanical device have been analytically developed and experimentally evaluated on the hydraulic test stand. The ORNL human extender/amplifier is shown in Fig. 11.

Fig. 11. The ORNL 1-D.O.F. human amplifier.
2.3.2 Human Extender/Amplifier Modeling

The governing linear equations for the human extender/amplifier will be derived in this section. The following derivation is valid for a symmetrical actuator with the servovalve spool at its center position. Using the center position as an operating point is a reasonable assumption for this system and its standard operating conditions. The human amplifier system at ORNL does not have a symmetrical actuator; however, this approximation is adequate to describe the dynamics of the system based on the experimental model verification demonstrated in the next section. Figure 12 is a free-body diagram of the human extender test stand.

Fig. 12. Free-body diagram of human extender test stand.

The following is a linear analysis of the model of the electrohydraulic system shown in Fig. 12. (See Ref. 2 for details and the list of symbols in Appendix A for definitions of terms.) Flow to the actuator, \( Q_L \), is related to command current to the servovalve, \( I \), with load pressure, \( P_L \) (which is similar to back emf for dc-motors) reducing the total flow,

\[
Q_L = K_q I - K_p P_L. \tag{2.3}
\]

For a hydraulic cylinder, the time rate of change of the actuator position, \( \dot{y} \), is related to the effective flow into the actuator, \( Q_L \), minus the amount that the fluid compresses (proportional to the time rate of change of the load pressure \( P_L \)) and minus the amount leaked across the cylinder seals (proportional to the load pressure \( P_L \)),

\[
A \ddot{y} = Q_L - \frac{V_T}{4 \beta_e} \frac{d P_L}{dt} - C_{tp} P_L. \tag{2.4}
\]
The actuator force, $F_{act}$, is equal to the dynamic forces, frictional losses, external load forces (i.e., contact with an environment), gravity (i.e., weight of the hardware), minus the hand forces (since the operator is in contact with the frame),

$$F_{act} = M \frac{d^2 y}{dt^2} + F_{frict} + F_{load} + F_{grav} - F_{hand}.$$  \hspace{1cm} (2.5)

Frictional forces can be divided into actuator frictional forces and everything else (i.e., friction associated with the carriage),

$$F_{frict} = F_{frict}^{act} + F_{frict}^{ee}.$$  \hspace{1cm} (2.6)

Load cell 1, placed between the cylinder and the frame, measures the cylinder actuator forces minus the actuator frictional forces with some sensor noise, $N_{LC1}$,

$$F_{LC1} = F_{act} - F_{frict}^{act} + N_{LC1}.$$  \hspace{1cm} (2.7)

Load cell 2, placed between the operator handle and the frame, measures the hand forces with some sensor noise, $N_{LC2}$,

$$F_{LC2} = F_{hand} + N_{LC2}.$$  \hspace{1cm} (2.8)

The total system is represented in the block diagram in Fig. 13.

---

**Fig. 13. Human extender/amplifier block diagram with controller.**

Some of the blocks on the diagram require further description. The $N$ and $B$ terms that add to the force of the hand and the actuator prior to their respective load cell measurements represent noise and bias respectively. The nonlinearity in the upper-right corner represents the environment; forces are zero while moving in free space and then contact is made with an environment represented by a linear spring with rate $K_s$. $G_c$ is a compensator that is to be
designed to stabilize and improve the performance of the human amplifier. \( B(s) \) is a transfer function containing valve flow pressure coefficient from Eq. 2.3 and leakage and compressibility term from Eq. 2.4. \( \text{NLK}_V \) is a nonlinear relationship between the amplifier frame motion and the human hand which will be discussed later. Note also that \( \alpha_p \) is the primary force reflecting gain and \( \alpha_{F} \) is the auxiliary force reflecting gain.

2.3.3 Parameters for Human Amplifier Model

Two tests were conducted to determine values for the physical plant model in the block diagram of Fig. 13. For the first test, a sinusoidal test signal is injected at \( E \) in Fig. 14.

\[
\begin{align*}
\frac{Y}{V}(s) &= \frac{K_d}{s [M V_T/4 \beta_e A^2] s^2 + [M (K_p + C_{tp})/A^2 + K_{visc} V_T/4 \beta_e A^2] + [1 + K_{visc} (K_p + C_{tp})/A^2]} \\
&= \frac{K_d A}{s [M V_T/4 \beta_e A^2] s^2 + [M (K_p + C_{tp})/A^2 + K_{visc} V_T/4 \beta_e A^2] + [1 + K_{visc} (K_p + C_{tp})/A^2]}.
\end{align*}
\]

Because of the low leakage and low viscous friction, \( K_{visc} (K_p + C_{tp}) \approx 0 \), Eq. (2.9) can be simplified to

\[
\frac{Y}{V}(s) \approx \frac{K_d A^2}{s [M V_T/4 \beta_e A^2] s^2 + [M (K_p + C_{tp})/A^2 + K_{visc} V_T/4 \beta_e A^2] + [1 + K_{visc} (K_p + C_{tp})/A^2]}.
\]

The model of Eq. 2.10 taken from typical data is shown in Fig. 15. This Bode plot is only for a fixed \( A_p \) of 1 in.; the frequency was swept through the discrete values shown by the x-marks (from 0.6 rad/s to almost 200 rad/s). For different amplitudes \( A_p \), the model changes because of the nonlinearities of the system (e.g., nonlinear orifice flow relationship in the servo valve, nonlinear friction, etc.); but the general trends are always the same.
Fig. 15. \( Y/V(s) \) transfer function (\( A_p \) was set for 1 in. travel). X's mark actual data points, and the lines, represent the fit to the data.

The second test to determine values for the physical plant model in the block diagram of Fig. 13 is based on inserting a sinusoidal command signal into the error signal, \( E \), and then measuring the force on the load cell between the actuator and the frame, \( F_{LC1} \). All positional and force control loops were opened. The transfer function between \( F_{LC1} \) and \( E \) (ref. Fig. 13), assuming \( \frac{K_{viss}}{A^2} (K_p + C_p) \equiv 0 \) as in Eq. 2.10,

\[
\begin{align*}
\frac{F_{LC1}(s)}{E} & \equiv \frac{\frac{K_q M}{R A} \left(s + \frac{K_{viss}}{M}\right)}{\frac{M V_T}{4 \beta_e A^2} s^2 + s \left[\frac{M}{A^2} (K_p + C_p) + \frac{K_{viss} V_T}{4 \beta_e A^2}\right] + 1}.
\end{align*}
\]

An example of typical data collected for this transfer function is shown in Fig. 16.
The objective of these tests and the prior measurements is to determine the coefficients in the models of Eqs. 2.10 and 2.11 and to ultimately obtain an estimate of the amount of uncertainty in these system models so that adequate margins could be inserted into the compensator design to accommodate these plant variations. Table 1 shows the values of similar coefficients taken from the models of Eqs. 2.10 and 2.11 and clearly illustrates the amount of variability resulting from the different models and measurements. These two model types were found to bound the data collected (as viewed from the Bode plots) for this test stand and will be used in the controller design.

Table 1. Coefficient values estimated for the models of Eqs. 2.10 and 2.11.

<table>
<thead>
<tr>
<th>Model Type</th>
<th>$\frac{M V_T}{4 \beta_e A^2}$</th>
<th>$\frac{M (K_p + C_{sp}) + K_{visc} V_T}{4 \beta_e A^2}$</th>
<th>$\frac{K_q M}{RA}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>For $\frac{Y}{V}(s)$ (Eq.2.10)</td>
<td>4.273E-5</td>
<td>2.189e-3</td>
<td>3.098</td>
</tr>
<tr>
<td>For $\frac{F_{LCI}(s)}{E(s)}$ (Eq.2.11)</td>
<td>1.859E-5</td>
<td>5.093e-3</td>
<td>4.862</td>
</tr>
</tbody>
</table>
2.3.4 Human Extender/Amplifier Control Objectives and Controller Design

Typical controllers drive an error function toward zero; therefore, to determine the controller objectives for the human amplifier, the appropriate error signal must be formulated. The overall objective of the human extender/amplifier is to magnify the operator’s hand force to overcome the dynamics of the mechanical system and load. This is represented by the following relationship:

\[ \alpha_F F_{\text{hand}} = M \frac{d\dot{y}}{dt} + F_{\text{frict}}^e + F_{\text{load}} + F_{\text{grav}} . \tag{2.12} \]

Combining the system dynamic and friction equations (Eqs. 2.5 and 2.6 respectively) one obtains the following:

\[ M \frac{d\dot{y}}{dt} + F_{\text{frict}}^e + F_{\text{load}} + F_{\text{grav}} = F_{\text{act}} + F_{\text{hand}} - F_{\text{act}}^f. \tag{2.13} \]

Recognizing that load cell 1 \((F_{\text{LC1}})\) measures the actuator forces, \(F_{\text{act}}\), minus the frictional losses, \(F_{\text{act}}^f\), and that load cell 2 \((F_{\text{LC2}})\) measures the hand forces, \(F_{\text{hand}}\), both with added noise (neglecting sensor bias), then

\[ M \frac{d\dot{y}}{dt} + F_{\text{frict}}^e + F_{\text{load}} + F_{\text{grav}} = F_{\text{LC1}} + F_{\text{LC2}} + \text{Sensor Noise}. \tag{2.14} \]

If sensor noise is ignored then combining Eqs. 2.12 and 2.14 and recognizing that \(F_{\text{hand}}\) is also \(F_{\text{LC2}}\) produces

\[ \alpha_F F_{\text{hand}} = \alpha_F F_{\text{LC2}} \equiv F_{\text{LC1}} + F_{\text{LC2}} . \tag{2.15} \]

or

\[ (\alpha_F - 1) F_{\text{LC2}} \equiv F_{\text{LC1}} . \tag{2.16} \]

The error equation can then be formulated as

\[ e = (\alpha_F - 1) F_{\text{LC2}} - F_{\text{LC1}} . \tag{2.17} \]

The controller's objective is to drive the error signal, \(e\), to zero. Only forces are being utilized for a human extender. This is in contrast to teleoperated systems, where either a position-position or a position-force type control architecture is employed. This error signal is shown in Fig. 13 as \(E\). Next, it will be shown that it is desirable to set the controller gain to as high a value as possible to mitigate the effect of the large cylinder friction.

One can show that the velocity of the cylinder and the actuator friction (modeled as a disturbance) can be related, assuming no contact with the environment or the operator \((F_{\text{hand}} = 0)\), as

\[ \frac{\dot{y}}{F_{\text{act}}^\text{frict}}(s) = \frac{-B}{A} \frac{K_q M}{R A} . \tag{2.18} \]
Equation 2.18 clearly shows that in the limit, as the compensator approaches an infinite gain ($G_c \to \infty$), the effect of friction due to the actuator will go to zero. This is the motivation for trying to keep the controller gain as high as possible over an acceptable range of frequencies.

2.3.5 Stability Problems with the Human Extender/Amplifier System

Three stability problems are encountered by the human extender system. The first is the free-space problem. This is where the device does not make contact with the environment or a human being. The second problem is the contact stability problem. For this condition, the device is making contact with the environment, but a human being is not attached to the device. The last stability problem is where contact is being made with the environment and the human being is attached to the device. The case where a human being is holding the handle and no contact is being made is a subset of the last problem and therefore will not be addressed.

1. Free-Space Problem (no contact with environment, either human or task):
   
   i. Set $F_{\text{frict}} + F_{\text{Load}} + F_{\text{grav}} = 0$, $B_{L1} = B_{L2} = 0$, $N_{L1} = N_{L2} = 0$, $N_{Lk} = 0$, $F_{\text{hand}} = 0$, and $F_{\text{frict}} = 0$.

   The resulting block diagram is shown in Fig. 17.

   ii. The transfer function between the error, $E$, and $Z$ (newly defined in the block diagram of Fig. 17) is

   $$Z(s) = \frac{\alpha_F \left( \frac{G_c K_d M}{RA} s \right)}{M s B + 1}$$

   (2.19)

   The Bode plot for Eq. 2.19 using the two sets of coefficients from the two different models in Table 1 is shown in Fig. 18.
Fig. 17. Block diagram for the free-space stability problem for the human extender/amplifier.

Fig. 18. Bode plot for $G_c(s) = 1$ and $\alpha_F = 1$ (the X's representing the actual data points have been removed to improve the quality of the figure).
Equation 2.19 is the open-loop transfer function. When the loop is closed, the transfer function between $F_{\text{hand}}$ and $Y$ is

$$
\frac{Y}{F_{\text{hand}}}(s) = \frac{G_c K_q}{RA} \left( \alpha_F + \frac{\alpha_F}{RA} - 1 \right) + \frac{B_A}{A} \frac{M}{s} B + \alpha_F \left( \frac{G_c K_q M}{RA} s + 1 \right). 
$$

(2.20)

2. Contact Stability Problem with $F_{\text{hand}} = 0$:
   i. Set $B_{\text{LC}1} = B_{\text{LC}2} = 0$, $N_{\text{LC}1} = N_{\text{LC}2} = 0$, $N_{\text{LK}_s} = 0$, and $F^{\text{act}}_{\text{frict}} = 0$.
   ii. A nonlinear relationship between $Y$ and an output $F_{\text{Load}}$ (as shown by the dashed line in the upper right corner of the block diagram in Fig. 13) represents the contact with the environment.
   iii. The transfer function between an input $Y$ and an output $F_{\text{Load}}$ is

$$
\frac{Y}{F_{\text{Load}}}(s) = \frac{- \left( B_A + \alpha_F \frac{G_c K_q}{RA} \right)}{M s B + \alpha_F \left( \frac{G_c K_q M}{RA} s + 1 \right)}. 
$$

(2.21)

The closed-loop control problem is shown in Fig. 19.

Fig. 19. Block diagram for the nonlinear contact problem #2 with environmental contact but no operator for the human extender/amplifier.

3. Contact Stability Problem with $F_{\text{hand}}$ as an Input:
   i. Set $B_{\text{LC}1} = B_{\text{LC}2} = 0$, $N_{\text{LC}1} = N_{\text{LC}2} = 0$, and $F^{\text{act}}_{\text{frict}} = 0$.
   ii. A nonlinear relationship between $Y$ and an output $F_{\text{Load}}$ (as shown by the dashed line in the upper-right corner of the block diagram in Fig. 13) represents the contact with the environment.
   iii. A nonlinear relationship exists between $Y$ and $F_{\text{hand}}$ and is represented by $N_{\text{LK}_v}$. An assumption will be made that this relationship can be approximated by a linear relationship (e.g., linear damper and spring) as $F_{\text{hand}} = - G_v(s) Y$. 

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iv. The transfer function between an input $F_{\text{Load}}$ and an output $\dot{Y}$ is

$$\frac{\dot{Y}}{F_{\text{Load}}} (s) = \frac{-\left(\frac{B}{A} + \alpha_F \frac{G_c K_q}{R A}\right)}{M \frac{s}{B} + \alpha_F \frac{G_c K_q M}{R A} + 1 + G_v \frac{G_c K_q \left(\alpha_F + \alpha'_F - 1\right) + B}{R A}}.$$  \hspace{1cm} (2.22)

This nonlinear problem is the same structurally as the one shown in Fig. 19.

To address problem 1, it is clear from Fig. 18 that in the low to mid frequency range the open loop system looks like a derivative operator (e.g., mass $\frac{d\dot{y}}{dt} = \text{force}$). To achieve higher gains over this frequency range, either an integrator or lag compensator is needed in the controller compensator $G_c(s)$

$$G_c(s) = \frac{K_c}{s}.$$ \hspace{1cm} (2.23)

In fact, it will be shown that an integrator for $G_c(s)$ will satisfy the next two problems as well. Setting the gain in Eq. 2.23, $K_c$, to 0.0028 provides at least a 25-dB-gain margin for problem 1. Integral compensation is not new to force control of manipulators; however, the main contribution of this analysis is that the nonlinear contact stability problem is formulated and the stability bounds and performances of the human extender/amplifier are tied to the test stand design parameters that were experimentally measured.

The describing function approach was found to be inadequate to solve these types of nonlinear control problems because of a violation of the Filter Hypothesis, that is, the output waveform is not dominated by the fundamental component; rather, it has a more extensive frequency content. Instead of using the describing function approach, the circle criterion was employed. According to the circle criterion, the transfer function $\hat{g}(j\omega) = \left[\frac{-\dot{Y}}{F_{\text{Load}}} (s) \frac{K_s}{s}\right]_{s = j\omega}$ must lie in the half-plane $\{s: \Re s > -1\}$ for stability to be guaranteed. It needs to be stressed that the circle criterion only states that if this region is avoided, then stability is assured; however, if this region is penetrated, then the circle criterion says nothing. In other words, it is sufficient to stay out of the region $\{s: \Re s > -1\}$ to ensure stability, but it is not necessary. The constraint of avoiding $\{s: \Re s > -1\}$ can be mapped to the Nichols chart, and this curve is shown in Fig. 20 as the open oval passing through the 0-dB, -180° point.

The load cell on the actuator has a stiffness of $2.8871 \times 10^7 \text{ N/m}$ (or $1.67 \times 10^5 \text{ lb/in.}$). Since the load cell is more compliant than the steel or aluminum of the actuator and frame, it is the critical design parameter. The environmental stiffness $K_s$ was selected to be 0.02 of the load cell compliance. Based on our experience, we could penetrate the circle criteria area and still maintain a stable system if we stayed away from the -1 point (e.g., 0-dB, -180°). Assuming a value of environmental stiffness of 0.02 of the load cell stiffness means that contact can only be made with relatively compliant objects such as rubber or cork. The obvious fix would be to add a compliant surface to the frame (i.e., end effector on a final design) such that hard contact with stiff objects such as metal is possible. This was the approach taken in the FARS project. The following discussion outlines an alternative solution for the hard contact problem (problem 3).
To address problem 3 (environmental contact and operator contact), it can be shown that for higher force reflection gains, $\alpha_F$, the model curves in Fig. 20 move lower along the gain axis. Moving the model curves down along the gain axis provides a greater margin between the model curves and the circle criteria stability boundary. This means that environments having larger stiffness can be accommodated. Mathematically, this becomes apparent by noting that $\alpha_F$ is in the denominator of Eq. 2.22. It can be shown that when the gains are around 200, hard contact with metals is possible without a compliant surface. Physically, this becomes apparent when one considers that with higher force gains the human operator can absorb more of the damping energy during contact. Once gains of up to 200 have been achieved, noise from the sensor becomes an issue and can no longer be neglected in the analysis. Section 3 will discuss an effective solution to the noise problem and other experimental observations.

2.4 ANALYSIS OF PARAMETERS THAT VARY AS A FUNCTION OF TEMPERATURE

When modeling hydraulic systems, it is important to recognize that the proper model is dependent upon the operating conditions, especially the temperature. Several of the fluid properties that influence the performance of a hydraulic manipulator vary as a function of temperature, and these are summarized in this section.

Density varies as a function of temperature and pressure, as is shown in Merritt:\(^2\)

$$\rho = \rho_0 \left[ 1 + \frac{1}{\beta} (P - P_0) + \alpha (T - T_0) \right]. \quad (2.23)$$
Viscosity and bulk modulus vary with temperature, and examples are shown in Tables 2 and 3.

Table 2. Viscosity as a function of temperature for Houghto-Safe® hydraulic fluid.

<table>
<thead>
<tr>
<th>Temperature (°C) (°F)</th>
<th>Viscosity (Centistokes)*</th>
<th>Viscosity (Saybolt Universal Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-18  0</td>
<td>648</td>
<td>3000</td>
</tr>
<tr>
<td>21 70</td>
<td>78</td>
<td>361</td>
</tr>
<tr>
<td>38 100</td>
<td>42</td>
<td>200</td>
</tr>
<tr>
<td>54 130</td>
<td>24</td>
<td>117</td>
</tr>
<tr>
<td>66 150</td>
<td>17</td>
<td>89</td>
</tr>
</tbody>
</table>

The equation relating Centistokes to Saybolt Universal Seconds is Centistokes = 0.216SUS - 166/SUS.

Table 3. Bulk modulus as a function of temperature for a MIL-H-5606B hydraulic fluid.

<table>
<thead>
<tr>
<th>Temperature (°C) (°F)</th>
<th>Bulk Modulus (kN/m²) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-18 0</td>
<td>2620 380,000</td>
</tr>
<tr>
<td>38 100</td>
<td>2413 350,000</td>
</tr>
<tr>
<td>93 200</td>
<td>2068 300,000</td>
</tr>
<tr>
<td>149 300</td>
<td>1379 200,000</td>
</tr>
<tr>
<td>204 400</td>
<td>620 90,000</td>
</tr>
</tbody>
</table>

Viscosity variation may be approximated by the following equation:

$$\mu = \mu_0 e^{-\lambda(T - T_0)} \quad \text{(2.24)}$$

where $\lambda$ is a fluid-dependent constant.

Pressure loss in bends, expansions, and entrances creates a rise in temperature and a resulting change in fluid properties. Temperature increases as a result of energy input through the pump but also through friction and energy loss through pipes and bends.
3. EXPERIMENTAL RESULTS

3.1 FLEXIBLE/PRISMATIC CHARACTERIZATION

3.1.1 Flexible/Prismatic Test Stand Mechanical Modeling

The flexible/prismatic test stand was designed to support ORNL's task cleanup and D&D activities. It was designed to carry realistic payloads with realistically sized hydraulic actuators. The prismatic joint of the flexible/prismatic test stand consists of a hardened steel tube with 1.0-in. OD and a 0.6 in. ID. This tube can extend from 12 to 60 in. In addition, the payload can vary from 10 to 75 pounds. With this range of payload and displacement, the arm can match the natural frequencies expected with the MLDUA. In addition, small displacements in the position of the prismatic actuator can provide dramatic variations in the natural frequency, as illustrated in Figs. 21 and 22. With the speed capacity of the prismatic and rotary joints, the natural frequency of the arm can vary by an order of magnitude over a very short range of motion in a very short time.

Figure 21 shows the variation of the flexible/prismatic test bed's link natural frequency as a function of payload and prismatic displacement. The stroke of the cylinder is 48 in. with the link length varying from 12 to 60 in.

Figure 22 shows the sensitivity of the flexible beam's natural frequency to variations in the prismatic displacement (in this case the payload is 25 lbf).

The rotary actuator on the flexible-prismatic test bed is a Parker HTR30 hydraulic rack and pinion rotary actuator. At 2000 psi, this actuator has a maximum torque capacity of 20,000 in.-lb. The prismatic joint is powered by a Parker Series EH hydraulic cylinder with a 2 in. bore. Its force capacity at 2000 psi is 6280 lb. Moog 760 series valves control the fluid flow. These high-bandwidth valves are relatively popular in the aircraft and robotics community. The valve on the rotary joint has a rated flow of 5 gpm, while the prismatic joint's flow is rated at 15 gpm. Vendor literature for this hardware is included in Appendix E.
Fig. 21. Analytical determination of the natural frequency as a function of length and payload for the flexible/prismatic test bed.
3.1.2 Flexible/Prismatic Test Stand Sensors

Lateral effect photodiodes provide a relatively new approach to measuring link end point position. These systems mount a laser diode on one end of the flexible link and a detector on the other end. The detector can measure the relative displacement of the diode, in either a line or a plane, with respect to the detector. The detector selected for the flexible/prismatic test bed is a Graseby Model 272. This detector has a 9.9° field of view. Future experiments will focus on using this detector for both vibration measurement and control. The goal of the experiments is to establish the benefit of tip deformation or position measurements in the control of flexible/prismatic manipulators. Specifications for another type of end point sensor are presented in Appendix D.
3.2 FLEXIBLE/PRISMATIC TEST STAND TEMPERATURE VARIATION EXPERIMENTS

A set of experiments was performed to characterize the response of the flexible/prismatic test bed to extended operation. One of the primary goals was to determine the sensitivity of the plant dynamics to temperature increases encountered during system warm-up and extended operation. Figure 23 contains experimentally measured temperature data at the hydraulic reservoir and at the actuator supply (measured right at the servovalve). These data were taken from a single day-long experiment with the flexible/prismatic test bed.

![Graph showing temperature variations of supply and reserve](image)

**Fig. 23.** Temperature vs time for a flexible/prismatic test bed extended operation experiment.

The figure shows the variation of reservoir and supply fluid temperature as a function of time. This increase in the temperature produced the effective variation in magnitude response evident in Figs. 24 and 25. The experiment consisted of running a consistent series of frequency response experiments. A program repetitively output 20 cycles of sine waves with frequencies of 0.4, 0.8, 1.0, 2.0, 5.0, 7.5, 10.0, and 12.5 Hz. During each cycle, the position response was measured, and the discrete fourier transform (DFT) of the frequency provided the corresponding magnitude and phase. Raw data for selected experiments are shown in Appendix C. The oscillation in the fluid temperature in the latter part of the experiment was due to a cooling effect in the hydraulic lines. The low-frequency moves are accompanied by significant motion of the actuator. As the frequencies of the commanded moves increase, the actuator response decreases in magnitude (refer to the Bode Plot of Fig. 24). This decrease in
actuator magnitude, which results from the natural inability of the dynamic system to track the high-frequency command, is associated with a concomitant decrease in the amount of fluid traveling through the lines from the reservoir to the valve and actuator. This lower flow is what causes the temperature to fall slowly since the fluid that rests in the hydraulic lines leading to the valve has time to cool and is not replaced by fresh, higher temperature fluid from the reservoir. Once the last high-frequency test of a particular series is completed, the lowest frequency test of the next set is conducted. The actuator can track this low-frequency command, resulting in large motion and large flow and accordingly, the temperature rises again. This explains the oscillating appearance of the supply temperature in Fig. 23.

Figure 24 shows the variation of the rotary hydraulic cylinder's magnitude response as the temperature of the hydraulic fluid varied from 25°C to ~50°C. The variation in the magnitude response provides the motivation for robust controller designs.
Figure 25 illustrates a three-dimensional plot of the magnitude response of the rotary hydraulic joint as a function of temperature and frequency. Appendix C includes the data and fits for selected temperature characterization experiments from this series of tests. Clearly, the main parameter that varied in the experiments is the magnitude of the response at low frequency. Referring to Eq. 2.4, one can see that the only parameter in the model that could vary as a function of temperature is the effective bulk modulus (also see Table 3). The conclusion is that the bulk modulus will decrease as a result of thermal expansion and that this change will reduce the stiffness and overall closed-loop bandwidth of a hydraulic servomechanism. When designing controllers for hydraulic manipulators, the variation of the plant with temperature (e.g., time) must be considered and appropriate measures taken. Cooling units can be added to the hydraulic power supply, and controllers should be formulated so that they are robust to temperature changes. In any event, adequate warm-up time should be allowed before operating, tuning, or calibrating a hydraulically actuated robot manipulator.
3.3 HUMAN EXTENDER/AMPLIFIER

The human extender/amplifier was experimentally evaluated in the laboratory and was shown to lift large loads with submillimeter accuracy. Force amplification ratios from 1 to 500 were achieved. More importantly, stable contact was achieved with environments of all stiffness ranging from free space, to foam, rubber and metal.

As the force amplification gain was increased to values above 100, it was observed that the noise level in the operator handle load cell (load cell 2) caused a noticeable random vibration. Typically, the auxiliary force reflection gain, $\alpha_F$, was set to a value of 1, and the primary force reflecting gain, $\alpha_F$, was set to the desired gain value. This was acceptable for total force reflecting gains (product of $1/\alpha_F$ and $\alpha_F$) under 100 where the handle load cell signal noise level did not cause a random vibration observable by the operator. If higher gains were required, a gain of 250 for example, $\alpha_F$ would have to be lowered to 0.1 and $\alpha_F$ set to 25. This allowed higher operating ranges at the expense of lowering the effective actuator friction reduction.

Contact stability was tested by driving the system against various objects of different stiffness. This system was able to go beyond a stiffness of 2% of the load cell stiffness (up to 5%) by increasing the compensator gain. Once the noise problem was overcome using the auxiliary gain method, contact with surfaces of rubber to hard metal was easily obtained.

To test the force reflection of the system, weights of 25- and 35-lb increments were added to the system. A spring scale was placed at the handle. By varying the force reflection ratio, the spring scale static position would change. Accuracies to the limit of the spring scale resolution were observed.

3.4 GENERAL EXPERIMENTAL COMMENTS AND OBSERVATIONS

The use of environmentally safe fluids is appealing from the standpoint of safety and compliance. Environmentally safe fluids are difficult to control because of low viscosity and increased air entrapment. ORNL has found Houghto-Safe® environmentally friendly fluid to be an acceptable compromise, and typical properties are provided in Table 4.

<table>
<thead>
<tr>
<th>Property</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1072 kg/m³</td>
<td>8.95 lb/lgal (0.0387 lb/in.³)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.074</td>
<td>1.074</td>
</tr>
<tr>
<td>Specific heat</td>
<td>2973 J/kg·°C</td>
<td>0.71 Btu/lbf·°F</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.45 W/m·°C</td>
<td>0.26 Btu/hr·ft·°F</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>1,965,000 N/m²</td>
<td>285,000 lbf/in.²</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>0.00061 1/°C</td>
<td>0.00034 1/°F</td>
</tr>
<tr>
<td>Pour point</td>
<td>-54°C</td>
<td>-65°F</td>
</tr>
<tr>
<td>Viscosity (21°C or 70°F)</td>
<td>78 Centistokes</td>
<td>89 SUS</td>
</tr>
</tbody>
</table>

Refer to Table 2 for the complete viscosity data.
4. FUTURE HYDRAULIC SYSTEMS

4.1 GUNITE AND ASSOCIATED TANKS

One of the largest problems facing DOE is the containment of hazardous waste stored in large underground nuclear waste storage facilities. Many of these facilities have contained hazardous materials for over 40 years. At the Hanford facility, there are 177 huge underground tanks of high-level nuclear waste, some of which have leaked or are building up heat or flammable gas. Access to these tanks is limited to ports and risers, generally 40 in. in diameter, that have been used for monitoring and sampling of the waste. Because of the uncertain integrity of the tanks, it is desirable to establish a method of deploying robots in the tanks with minimal impact on the tank's structure. One option is to design a long, slender robot that can be deployed through the existing ports and risers.

At ORNL, there are underground waste storage facilities as well. Fortunately, the number of tanks and their level of radiation is far below levels at the Hanford facility. A current project at the Robotics and Process Systems Division (RPSD) at ORNL consists of constructing a system that can go into an underground storage facility and safely extract waste for reprocessing and safer storage. This system consists of two long-reach manipulators deployed simultaneously in a tank. The first manipulator, the MLDUA, has 8-D.O.F. and a payload capacity of 250 lb. A second arm, the hose management arm (HMA), has 4-D.O.F. It carries a confined sluicing end-effector (CSEE) that acts as a cutting jet and vacuum for waste removal. The strategy is to have the MLDUA grasp the CSEE and move through the tank, extracting material. Figure 26 illustrates a conceptual image of the gunite tanks and the associated hardware. (Gunite is a concrete-like material.)

4.2 APPLICATION OF DAWM TO THE CP-5 REACTOR AT ANL

The most pressing application of the techniques described herein are for the accurate control of the DAWM described in the Introduction. This system is being deployed in the CP-5 reactor at ANL. The basic degrees-of-freedom of the DAWM arms are all hydraulically actuated and must be operated with some limited robotics capabilities. Accurate control of these joints will require a complete understanding of the hydraulic issues discussed in this report.

4.3 SCHILLING 7F

The 6-D.O.F., multiplaner, teleoperated, flexible controls Schilling 7F test bed has been transferred to the Cold Test Facility (CTF) at ORNL. This facility is a mockup of the ORNL Gunite tanks. It includes a real control room, a mock tank, mock waste, vision systems, and other support hardware. The Schilling 7F test bed is being used for control system integration prior to receiving the Modified Light Duty Utility Arm (MLDUA) that is to be inserted into the CTF and eventually into the Gunite tanks. One of the first tasks is to integrate path planning and control routines for waste cleanup and to integrate T. J. Tarn's newly developed event-based controllers.
4.4 DEXTEROUS MANIPULATION OF HEAVY PAYLOADS

Dexterous manipulation of heavy payloads (DMHP) is a new application area for hydraulic manipulators. Basically, DMHP is defined as systems with payload/weight ratios greater than 1 and positioning accuracy/payload ratios less than $10^{-6}$ m/kg. These systems appear in nature as insects and as large animals (e.g., rhinoceroses and elephants) but they have no parallel in the machine world. Present manipulator systems have precision accuracy/payload ratios that range around $10^{-2}$ m/kg for electric robots to $10^{-1}$ m/kg for conventional machines and earthmoving equipment. Aiming for a goal of $10^{-6}$ m/kg for a DMHP machine will require careful analysis and design of hydraulic control systems. The design and modeling techniques developed herein will contribute to this goal.

Fig. 26. Tank waste removal hardware for the GAAT cleanup effort at ORNL.
5. CONCLUSIONS

ORNL has extensive experience in the design, analysis, and control of hydraulic manipulators. ORNL has over a decade of experience in developing hydraulic systems for a number of applications including mobile robotics, robotic arms, and new concept systems. To support the development and deployment of the new hydraulic manipulators, ORNL has outfitted a significant experimental laboratory and has developed the software capability for research into hydraulic manipulators, hydraulic actuators, hydraulic systems, modeling of hydraulic systems, and hydraulic controls. The three manipulator systems in the Hydraulics Laboratory at ORNL and the hydraulics modeling capability have been used to extend ORNL's experience and hardware capability in hydraulics. The 6-D.O.F., multiplaner, teleoperated, flexible controls test bed has been used for basic controller development and as a systems integration tool for the gunite tank efforts. The 2-D.O.F. flexible/prismatic test bed has been used for the development of waste tank cleanup manipulator controls, thermal studies, system characterization, and manipulator tracking. One of the primary sets of tests with the 2-D.O.F. flexible/prismatic test bed was the extended operational experiments where the hydraulic system model was determined as a function of time (temperature). Finally, the human amplifier test bed was used for the development of an entirely new class of teleoperated systems, including not only amplifier systems but also deamplifier systems as well. These experiences and the existing hardware and software infrastructure give ORNL an unmatched capability in hydraulic manipulator design and analysis.
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REFERENCES


APPENDIX A
LIST OF SYMBOLS

\[ A = \text{effective cylinder area} \ (\text{in.}^2) \]
\[ A_p = \text{amplitude} \ (\text{in.}) \text{ for sinusoidal input functions} \]
\[ B(s) = \frac{K_p + C_p V_T}{A} + \frac{4 \beta_c A}{s} \quad \text{transfer function defined for compactness} \]
\[ B_{LC1} = \text{bias voltage for load cell 1} \ (\text{V}) \]
\[ B_{LC2} = \text{bias voltage for load cell 2} \ (\text{V}) \]
\[ B_m = \text{motor viscous damping} \ (\text{in.-lb}_f\cdot\text{s}) \]
\[ B_p = \text{piston viscous damping} \ (\text{lb}_f/\text{in.}/\text{s}) \]
\[ C_{tm} = \text{total leakage coefficient for a rotary motor} \ (\text{in.}^3/\text{s}/\text{psi}) \]
\[ C_{tp} = \text{total leakage coefficient for a piston} \ (\text{in.}^3/\text{s}/\text{psi}) \]
\[ D_m = \text{volumetric displacement for a rotary motor} \ (\text{in.}^3/\text{rad}) \]
\[ \frac{\text{d}}{\text{dt}} = \text{time derivative} \]
\[ E \text{ or } e = \text{error signal} \ (\text{V}) \]
\[ F_{act} = \text{actuator force} \ (\text{lb}_f) \]
\[ F_{frict} = \text{total friction force} \ (\text{lb}_f) \]
\[ F_{frict}^{\text{act}} = \text{actuator friction} \ (\text{lb}_f) \]
\[ F_{frict}^{\text{ce}} = \text{friction of carriage} \ (\text{lb}_f) \]
\[ F_{grav} = \text{gravity force} \ (\text{lb}_f) \]
\[ F_{hand} = \text{hand force} \ (\text{lb}_f) \]
\[ F_{LC1} = \text{load cell 1 force} \ (\text{lb}_f) \]
\[ F_{LC2} = \text{load cell 2 force} \ (\text{lb}_f) \]
\[ F_{Load} = \text{load force} \ (\text{lb}_f) \]
\[ g(jw) = \text{circle criterion transfer function} \]
\[ G_1(s), G_2(s) = \text{arbitrary transfer functions} \]
\[ G_c(s) = \text{compensator transfer function} \]
\[ G_4(s) = \text{linear transfer function modeling relationship between Operator and human extender/amplifier} \]
\[ I = \text{electrical current} \ (\text{A}) \]
\[ J_T = \text{motor and load inertia reflected at the motor shaft} \ (\text{in.-lb}_f\cdot\text{s}^2) \]
\[ K_p = \text{valve flow pressure coefficient} \ (\text{in.}^3/\text{s}/\text{psi}) \]
\[ K_{PTm} = \text{total flow pressure coefficient for a rotary motor} \ (\text{in.}^3/\text{s}/\text{psi}) \]
\[ K_{PTp} = \text{total flow pressure coefficient for a piston} \ (\text{in.}^3/\text{s}/\text{psi}) \]
\[ K_q = \text{valve flow gain with current as command} \ (\text{in.}^3/\text{s}/\text{A}) \]
\[ K_{q1} = \text{valve flow gain with valve position as command} \ (\text{in.}^3/\text{s}/\text{in.}) \]
KS = environment stiffness (lbf/in.)
K visc = viscous coefficient (lbf/in./s)
M = mass of load (lbm)
NLCl = noise voltage of load cell 1 (V)
NLCl = noise voltage of load cell 2 (V)
NLKs = nonlinear spring (lbf/in.)
NLKv = nonlinear block (lbf/in./s)
PL = load pressure (psi)
QL = effective flow (in.³/s)
R = electrical resistance (Ω)
s = Laplace transform variable
T = temperature (°F)
T o = nominal temperature (°F)
VT = total volume (in.³)
V = voltage (V)
xv = valve position (in.)
Y or y = actuator position (in.)
Y or y = actuator velocity (in./s)
Z = modified load cell force (lbf)
α = cubical expansion coefficient (1/°F)
αF = force gain
αF = auxiliary force gain
β = bulk modulus (psi)
βo = effective bulk modulus (psi)
θm = rotary motor position (rad)
λ = viscosity temperature constant (1/°F)
ρ = density (lbm/ft³)
ρo = density at nominal condition (lbm/ft³)
μ = absolute viscosity (lbf·s/in.²)
μo = absolute viscosity at T o (lbf·s/in.²)
APPENDIX B

GOVERNING EQUATIONS FOR HYDRAULIC DYNAMICS

B.1 INTRODUCTION

A typical linear actuator system is shown in Fig. B.1. It is basically a three-land four-way critical center spool valve that controls the flow of pressurized oil to and from the power cylinder. The power cylinder is solidly connected to a purely inertial load whose motion is opposed by nonlinear friction forces. In the case of the rotary actuator, the piston will have rotary motion, as opposed to linear motion and the rotary motor would generate a torque instead of a force.

\[
\begin{align*}
Q_s & \quad \text{Supply Flow Rate} \\
Ps & \quad \text{Supply Pressure} \\
Q_2 & \\
Q_1 & \\
P_2 & \\
P_1 & \\
x_v & \\
x_p & \\
B_p & \\
k_p & \\
M_t & \\
\end{align*}
\]

Fig. B.1. Model of hydraulic piston used for explanation of governing equations.
B.2 VALVE EQUATIONS

To develop the combined servovalve and actuator model, we will consider two cases: one where the servovalve spool position $x_v$ is positive and the other where $x_v$ is negative.

Case I: Extension Stroke ($x_v \geq 0$)

Assuming that there is symmetry in the construction of the servovalve and orifice geometries, the flow rates $Q_1$ and $Q_2$ are

$$Q_1 = C_d A \frac{2}{\sqrt{\rho}} (P_s - P_1)$$

$$Q_2 = C_d A \frac{2}{\sqrt{\rho}} (P_2 - P_1) \quad \text{(B.1a & B.1b)}$$

where $C_d$ is the discharge coefficient (as defined by Merritt), $\rho$ is the fluid mass density, and $A$ is the orifice area. With the assumption of linear valve displacement characteristics, Eqs. (B.1a) and (B.1b) can be rewritten in terms of spool position, $x_v$, as

$$Q_1 = C_d x_v \sqrt{(P_s - P_1)}$$

$$Q_2 = C_d x_v \sqrt{(P_2 - P_1)} \quad \text{(B.2a & B.2b)}$$

which are normalized to yield

$$q_1 = C_{d\text{eff}} x_{v\text{norm}} \sqrt{(1 - P_1)}$$

$$q_2 = C_{d\text{eff}} x_{v\text{norm}} \sqrt{(P_2 - P_1)} \quad \text{(B.3a & B.3b)}$$

where

$$q_1 = \frac{Q_1}{Q_s}, \quad q_2 = \frac{Q_2}{Q_s}, \quad p_1 = \frac{P_1}{P_s}, \quad p_2 = \frac{P_2}{P_s}, \quad p_r = \frac{P_r}{P_s},$$

$$x_{v\text{norm}} = \frac{x_v}{x_v \text{max}}, \quad C_{d\text{eff}} = C_d \frac{\sqrt{P_s}}{Q_s} x_v \text{max}.$$
Case II: Retraction Stroke \((x_v < 0)\)

In this case, Eqs. (B.3a) and (B.3b) become

\[
q_1 = C_{d_{xyf}}x_{vnorm}\sqrt{(p_1 - p_r)} \quad (B.4a & B.4b)
\]

\[
q_2 = C_{d_{xvf}}x_{vnorm}\sqrt{(1 - p_2)}.
\]

In Eqs. (B.3) and (B.4), the sign of \(x_v\) determines the direction of flow. The flow saturation effect can be modeled as

\[
x_{vnorm} = \begin{cases} 
  x_{vnorm} & \text{for } |x_{vnorm}| < 1 \\
  x_{vmax} & \text{for } |x_{vnorm}| \geq 1 
\end{cases} \quad (B.5)
\]

The servovalve dynamics are modeled as

\[
\frac{d}{dt}\left(\frac{x_v}{x_{vmax}}\right) = \frac{x_{vmax}}{\tau} \left(\frac{x_{vl}}{x_{vmax}} - \frac{x_v}{x_{vmax}}\right), \quad (B.6)
\]

where \(x_{vl}, x_v\) are the desired and actual servovalve positions respectively.

**B.3 LINEAR ACTUATOR EQUATIONS**

The continuity equation to each piston chamber can be written as:

\[
\dot{P}_1 = \frac{\beta_1}{V_1} \left[Q_1 - A_{p1} \dot{x}_p - C_{q}(P_1 - P_2) - C_{p}P_1 \right] \quad (B.7a & B.7b)
\]

\[
\dot{P}_2 = \frac{\beta_2}{V_2} \left[-Q_2 - A_{p2} \dot{x}_p + C_{q}(P_1 - P_2) - C_{p}P_2 \right],
\]

where

- \(V_1\) = volume of forward chamber (includes valve, connecting line, and piston volume), in.\(^3\);
- \(V_2\) = volume of return chamber (includes valve, connecting lines, and piston volume), in.\(^3\);
- \(C_{q}\) = internal or cross-port leakage coefficient of piston, in.\(^3\)/s-psi;
- \(A_{p1}\) = area of piston on side 1, in.\(^2\);
- \(A_{p2}\) = area of piston on side 2, in.\(^2\);
- \(x_p\) = displacement of piston, in.
The volumes of the piston chambers may be written

\[ V_1 = V_{01} + A_{p1}x_p \]

\[ V_2 = V_{02} - A_{p2}x_p, \]

where \( V_{01} \) is the initial volume of forward chamber in.\(^3\) and \( V_{02} \) is the initial volume of return chamber, in.\(^3\).

The Eqs. (B.7a) and (B.7b) are normalized to yield

\[ \dot{p}_1 = \frac{\beta_s}{V_1} \left[ q_1 \left( \frac{q_s}{p_s} \right) - \left( \frac{A_{p1}}{p_s} \right) \ddot{x}_p - C_{ip} (p_1 - p_2) - C_{ip} p_1 \right] \]

\[ \dot{p}_2 = -\frac{\beta_s}{V_2} \left[ q_2 \left( \frac{q_s}{p_s} \right) - \left( \frac{A_{p2}}{p_s} \right) \ddot{x}_p - C_{ip} (p_1 - p_2) + C_{ip} p_2 \right], \]

where \( p' s \) and \( q' s \) are as defined above.

The force generated or developed by the piston is

\[ F_{gen} = A_{p1} p_1 - A_{p2} p_2. \]  \hspace{1cm} (B.9)

The nonlinear friction model can be represented as shown in Fig. B.2, where theoretically, the switchover from the static friction \( F_s \) to dynamic friction \( F_c \) is considered to occur at \( |\dot{x}_p| = 0^+ \). However, this causes some instability when the model is to be solved by numerical techniques. Therefore, the switchover is assumed to take place at a certain velocity \( |\dot{x}_p| = D\nu \), which is chosen in order to give sufficient numerical stability.

The friction force \( F_f \) can be modeled as follows:

\[ F_f = \begin{cases} 
F_{gen} & \text{for } |F_{gen}| < |F_s| \text{ and } |\dot{x}_p| \leq D\nu \\
F_s \text{sign}(F_{gen}) & \text{for } |F_{gen}| > |F_s| \text{ and } |\dot{x}_p| \leq D\nu \\
F_c \text{sign}(F_{gen}) & \text{for } |\dot{x}_p| > D\nu 
\end{cases} \]

(B.10)

which is shown in Fig. B.2.
Assuming inertia load and nonlinear friction, the force equation can be described by

\[ F_{\text{gen}} = M_i \ddot{x}_p + B_p \dot{x}_p + F_f, \]  

(B.11)

where \( M_i \) is the total mass of piston and load referred to piston (lb-s\(^2\)/in.) and \( B_p \) is the viscous damping coefficient of piston and load (lb-s/in.).

For a bore diameter of \( D \) (in.), a piston rod diameter of \( d \) (in.), and a friction factor \( F_p \), the coulomb friction force may be obtained from

\[ F_c = 12d + 30F_p d + 6F_p D. \]  

(B.12)

The stiction force is calculated by applying a correction factor of \( F_{\text{corr}} \) to friction factor \( F_p \). Hence the stiction force equation becomes

\[ F_s = 12d + 30F_{\text{corr}} F_p d + 6F_{\text{corr}} F_p D. \]  

(B.13)

The correction factor for low-friction-type seals used in this actuator is 1.0.
B.4 ROTARY ACTUATOR EQUATIONS

The same servovalve models apply in the case of the rotary actuator. The continuity equations for piston motors are given by

\[ \dot{p}_1 = \frac{\beta_s}{V_1} \left[ q_1 \left( \frac{Q_s}{P_s} \right) - \left( \frac{D_m}{P_s} \right) \omega_m - C_m (p_1 - p_2) - C_{em} p_1 \right] \]

\[ \dot{p}_2 = -\frac{\beta_s}{V_2} \left[ q_2 \left( \frac{Q_s}{P_s} \right) - \left( \frac{D_m}{P_s} \right) \omega_m - C_m (p_1 - p_2) + C_{em} p_1 \right], \]

where \( D_m \) is the volumetric displacement of the motor (in.\(^3\)/rad) and \( \omega_m \) is the angular velocity of the motor shaft (rad/s) and other variables are similar to those defined in the linear actuator case.

The two volumes may be expressed by

\[ V_1 = V_0 + D_m \theta_m \]

\[ V_2 = V_0 - D_m \theta_m, \]

where \( \theta_m \) is the angular displacement of the motor. The torque generated by the motor becomes

\[ T_{gen} = D_m (p_1 - p_2). \]

The load equation can be written as

\[ T_{gen} = J_t \dot{\theta}_m + B_m \dot{\theta}_m + T_f, \]

where \( J_t \) is the load inertia, \( B_m \) is the viscous friction, and \( T_f \) is the nonlinear friction torque.

A similar model, as in the case of linear actuator, is assumed for the nonlinear friction torque. Nonlinear friction torques \( T_c \) and \( T_s \) are assumed equal and are calculated from the given breakaway force.
APPENDIX C

RAW DATA FOR SELECTED EXPERIMENTS FROM THE EXTENDED OPERATION EXPERIMENTS WITH THE FLEXIBLE/PRISMATIC TEST BED

Table C.1. Raw data from temperature variation study for the rotary actuator of the flexible/prismatic test bed
Column 1 is the input sine wave frequency (~1-inch position command), column 2 is the supply temperature, column 3 is the reservoir temperature, column 4 is the magnitude, and column 5 is the phase of the Bode plot model.

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<td>-120.1499</td>
</tr>
</tbody>
</table>
Table C.1 (cont.) Raw data from temperature variation study for the rotary actuator of the flexible/prismatic test bed
Column 1 is the input sine wave frequency (~1-inch position command), column 2 is the supply temperature, column 3 is the reservoir temperature, column 4 is the magnitude, and column 5 is the phase of the Bode plot model.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Supply Temp</th>
<th>Reservoir Temp</th>
<th>Magnitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0000</td>
<td>45.4000</td>
<td>46.3000</td>
<td>0.0199</td>
<td>-169.1051</td>
</tr>
<tr>
<td>7.5000</td>
<td>45.2000</td>
<td>46.3000</td>
<td>0.0115</td>
<td>171.9688</td>
</tr>
<tr>
<td>10.0000</td>
<td>45.1000</td>
<td>46.4000</td>
<td>0.0066</td>
<td>146.5064</td>
</tr>
<tr>
<td>12.5000</td>
<td>45.1000</td>
<td>46.4000</td>
<td>0.0029</td>
<td>136.8753</td>
</tr>
<tr>
<td>0.4000</td>
<td>49.8000</td>
<td>51.8000</td>
<td>0.4865</td>
<td>-67.9928</td>
</tr>
<tr>
<td>0.8000</td>
<td>50.1000</td>
<td>51.9000</td>
<td>0.2776</td>
<td>-87.7229</td>
</tr>
<tr>
<td>1.0000</td>
<td>50.2000</td>
<td>51.9000</td>
<td>0.2275</td>
<td>-93.7230</td>
</tr>
<tr>
<td>2.0000</td>
<td>50.1000</td>
<td>52.0000</td>
<td>0.1409</td>
<td>-119.6014</td>
</tr>
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<td>5.0000</td>
<td>49.8000</td>
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<td>0.0180</td>
<td>-168.1353</td>
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<td>7.5000</td>
<td>49.7000</td>
<td>52.1000</td>
<td>0.0115</td>
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<tr>
<td>10.0000</td>
<td>49.4000</td>
<td>52.2000</td>
<td>0.0080</td>
<td>147.8011</td>
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<tr>
<td>12.5000</td>
<td>49.4000</td>
<td>52.2000</td>
<td>0.0042</td>
<td>141.0822</td>
</tr>
</tbody>
</table>
This appendix includes some data on one commercially available 6-D.O.F. position sensor that might be applicable to the flexible/prismatic test stand.

Vendor: Ascension Technology

Product Name: Flock of Birds

Description: This is a 6-D.O.F. position sensor that is based upon a pulsed DC magnetic field. There is one transmitter (approximately a 12 inch cube) and up to 60 receivers (approximately a 1 inch cube). For example, one can track up to 60 of these sensors (relative to the big cube). Because of the pulsed field, the sensor is somewhat sensitive to metallic objects (it receives some interference due to eddy currents), but it is not as bad as ac field technology (e.g., Polhemus sensors).

Specifications:

- Range: ± 3 ft. (translation) ± 180° (azimuth, roll) ± 90° (pitch)
- Accuracy: 0.1 in. RMS (translation) 0.5° (rotation)
- Resolution: 0.03 in.
- Cost: ~$2500

This sensor has extended range transmitters that go up to ± 12 ft. with a degradation in accuracy and resolution.
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APPENDIX E

VENDOR LITERATURE FOR HARDWARE TEST STANDS
760 Series Servo valves

The 760 Series is a high performance, two-stage design that covers the range of rated flows from 1 to 15 gpm at 1000 psi valve drop. The output stage is a closed center, four-way, sliding spool. The pilot stage is a symmetrical double-nozzle and flapper, driven by a double air gap, dry torque motor. Mechanical feedback of spool position is provided by a cantilever spring. The valve design is simple and rugged for dependable, long life operation.

Specifications:

Fluid Supply: 760 Series Servo valves are intended to operate with constant supply pressure.

Supply Pressure:
- Minimum: 200 psi (14 bar)
- Maximum Standard: 3500 psi (245 bar)
- Maximum (special order): 5000 psi (350 bar)

Proof Pressure:
- 150% of supply pressure at P port
- 100% of supply pressure at R port

Fluid:
- Compatible with common hydraulic fluids
- Recommended viscosity range: 60-450 SUS@ 100°F (10-97 cSt@38°C)

Cleanliness Level:
- ISO DIS 4406 code 16/13 max.
- 14/11 recommended

Operating Temperature:
- Minimum: -40°F (-40°C) (maximum fluid viscosity: 6000 SUS)
- Maximum: +275°F (+135°C)

Rated Flow Tolerance: ±10%

Symmetry: < 10%

Hysteresis: < 3%

Threshold: < 1/2%

Null Shift:
- with temperature, 100°F variation: < 2%
- with acceleration to 10g: < 2%
- with supply pressure 1000 psi change: < 2%
- with back pressure 0 to 500 psi: < 2%

Frequency Response: Typical response characteristics for 760 Series Servo valves are shown in Figures 1, 2, and 3.

Step Response: Typical transient responses of 760 Series Servo valves are shown in Figure 4. The straight line portion of the response represents saturation flow from the pilot stage which will increase with higher supply pressures.
760 Series Servovalves

The 760 Series is a high performance, two-stage design that covers the range of rated flows from 1 to 15 gpm at 1000 psi valve drop. The output stage is a closed center, four-way, sliding spool. The pilot stage is a symmetrical double-nozzle and flapper, driven by a double air gap, dry torque motor. Mechanical feedback of spool position is provided by a cantilever spring. The valve design is simple and rugged for dependable, long life operation.

Specifications:

Fluid Supply: 760 Series Servovalves are intended to operate with constant supply pressure.

Supply Pressure:
- Minimum: 200 psi (14 bar)
- Maximum Standard: 3500 psi (245 bar)
- Maximum (special order): 5000 psi (350 bar)

Proof Pressure:
- 150% of supply pressure at P port
- 100% of supply pressure at R port

Fluid:
- Compatible with common hydraulic fluids
- Recommended viscosity range: 60-450 SUS (10²-97 cSt)
- Operating Temperature:
  - Minimum: -40°F (-40°C) (maximum fluid viscosity: 6000 SUS)
  - Maximum: +275°F (+135°C)

Rated Flow Tolerance: ±10%

Symmetry: < 10%

Hysteresis: < 3%

Threshold: < 1/2%

Null Shift:
- with temperature, 100°F variation: < 2%
- with acceleration to 10g: < 2%
- with supply pressure 1000 psi change: < 2%
- with back pressure 0 to 500 psi: < 2%

Frequency Response: Typical response characteristics for 760 Series Servovalves are shown in Figures 1, 2, and 3.

Step Response: Typical transient responses of 760 Series Servovalves are shown in Figure 4. The straight line portion of the response represents saturation flow from the pilot stage which will increase with higher supply pressures.

<table>
<thead>
<tr>
<th>Model</th>
<th>Response</th>
<th>Rated Flow (1000 psi)</th>
<th>Internal Leakage (1000 psi)</th>
<th>Rated Current (parallel coils)</th>
<th>Coil Nom. Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>760-100A</td>
<td>Std.</td>
<td>1.0</td>
<td>0.17</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>760-101A</td>
<td>Std.</td>
<td>2.5</td>
<td>0.22</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>760-102A</td>
<td>Std.</td>
<td>3.5</td>
<td>0.30</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>760-103A</td>
<td>Std.</td>
<td>5.0</td>
<td>0.45</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>760-104A</td>
<td>Std.</td>
<td>10.0</td>
<td>0.65</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>760-105A</td>
<td>Std.</td>
<td>15.0</td>
<td>0.95</td>
<td>15</td>
<td>200</td>
</tr>
</tbody>
</table>

Optional designs are available with intrinsically safe coils (FM approved), and/or special spool/bushing gap configurations. Available seal materials: BUNA (Std.), VITON or EPR.
Standard Electrical Configuration

Torque motor coils

Connector pins

External connections and electrical polarity for flow out control port No. 2 are:
- Single coil: A+, B- or C+, D-
- Series coils: tie B to C; A+, D-
- Parallel coils: tie A to C and B to D, A & C+, B & D-

Accessories:

Flushing Block: PN 23718-1K1
Mating Electrical Connector: PN 49054F14S2S (MS3106F14S-2S)
Suggested Mounting Bolts: PN A31324-228B
5/16 - 18NC x 1 3/4 long
Socket Head Cap Screw
Subplate: 3000 psi 5000 psi
4 port PN 43586 -1 -5
5 port PN 43586 -4 -7
System filters available. Call factory for details or see brochure #605.

Notes:

Valve Weight: 2.3 lb (1.03 kg)
Aux. Pilot Pressure Port: Optional
Null Adjust: Flow out of control port No. 2 will increase with clockwise rotation of null adjust screw (3/32 hex key).
Surface Finish: Surface to which valve is mounted requires \( \frac{1}{8} \) (0.03) TIR.
Standard Electrical Configuration

760 Series

External connections and electrical polarity for flow out control port No. 2 are:
- Single coil: A+, B-; or C+, D-
- Series coils: tie B to C: A+, D-
- Parallel coils: tie A to C and B to D: A & C+, B & D-

Accessories:
- Flushing Block: PN 23718-1K1
- Mating Electrical Connector: PN 49054F14S2S (MS3106F14S-2S)
- Suggested Mounting Bolts: PN A31324-228B 5/16 - 18NC x 1-3/4 long Socket Head Cap Screw
- Subplate: 3000 psi 5000 psi 4 port PN 43586 -1 -5 5 port PN 43586 -4 -7

System filters available. Call factory for details or see brochure #605.

Notes:
- Valve Weight: 2.3 lb (1.03 kg)
- Subplate O-Ring Size: 0.070 [1.78] sect. x 0.426 [10.82] I.D. (universal size -013)
- Aux. Pilot Pressure Port: Special order
- Null Adjust: Flow out of control port No. 2 will increase with clockwise rotation of null adjust screw (3/32 hex key).
- Surface Finish: Surface to which valve is mounted requires [VV] finish, flat within 0.001 [0.03] TIR.

Moog Controls Inc. • East Aurora, NY 14052-3300 • 716/655-3000 • FAX: 716/655-1803
Model NF122-202A1 Servoamplifier

This circuit card is designed to drive servovalves or proportional valves in closed-loop servosystems. It provides any combination of proportional, integral, and derivative control (PID). It may also be used as a simple voltage-to-current converter to drive servovalves.

The NF122-202A1 Servoamplifier is a form-fit-function replacement for the F122-202A001.

Features

PID Control
- Jumper-selectable proportional, integral, and derivative control
- Independent integral and derivative gain adjustments
- Adjustable low-pass filter on derivative control
- Easily-accessible integrator reset function

Error-Summing Input Stage
- Three standard inputs can be reconfigured for differential input
- Independent gain, bias, trim, and scale potentiometers
- Summed error easily accessible for monitoring

Front-Panel Adjustments
- Provide quick access to gains, scales, bias, and dither

Front-Panel Test Points
- Allow for fast & easy setup, test, & monitoring of parameters

Dither Generator
- Jumper-selectable with adjustable frequency and amplitude

Current or Voltage Drive
- Jumper-selectable with overcurrent protection

SPDT Relay Section
- Energized by high (5 to 15 Vdc) or low (0 Vdc) logic signal
- Used for integrator reset, signal switching, or other functions

Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional Gain</td>
<td>5 to 200 mA/V</td>
</tr>
<tr>
<td>Integral Gain</td>
<td>5 to 3,000 mA/V-sec</td>
</tr>
<tr>
<td>Derivative Gain</td>
<td>0.02 to 8 mA-sec/V</td>
</tr>
<tr>
<td>Current Output</td>
<td>to ± 50 mA into 130Ω coil</td>
</tr>
<tr>
<td>Voltage Output</td>
<td>to ± 10 Vdc nominal</td>
</tr>
<tr>
<td>Input Levels</td>
<td>to ± 15 Vdc on terminals 3 and 7 to ± 120 Vdc on terminal 9</td>
</tr>
<tr>
<td>Drift</td>
<td>≤ 0.1 mV/°C from 10°C to 50°C (with 100KΩ inputs and proportional gain at 50 mA/V)</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>10°C to 50°C (50°F to 120°F)</td>
</tr>
<tr>
<td>Frequency Response</td>
<td>-3 dB @ ≥ 800 Hz (1 Henry load)</td>
</tr>
<tr>
<td>Linearity</td>
<td>± 3% full scale</td>
</tr>
<tr>
<td>Dither</td>
<td>25 to 300 Hz, 0 to 20 mA p-p</td>
</tr>
<tr>
<td>Relay</td>
<td>contacts: ≤ 2 A/24 Vdc consumption: 15 mA from +24 Vdc line</td>
</tr>
<tr>
<td>Connector</td>
<td>DIN 41612 style C</td>
</tr>
<tr>
<td>Form Factor</td>
<td>Eurocard 100 x 160 mm, 7HP, 3U</td>
</tr>
<tr>
<td>Weight</td>
<td>0.36 lb (0.16 kg)</td>
</tr>
</tbody>
</table>

Adjustments

P1 Bias  Changes bias voltage at input (summing) stage. Turn CW for positive input bias voltage. Adjust for desired offset between command and feedback.
P2 Gain  Changes proportional gain of input (summing) stage. Also changes integral and/or derivative gains if jumpers I or D are on. Turn CW to increase gain. Adjust for system stability.
P3 Dither Frequency  Turn CW to increase frequency. Adjust for a frequency appropriate for system dynamics.
P4 Dither Amplitude  Turn CW to increase amplitude. Adjust for desired dither current amplitude, typically ±10% of rated current. Note: jumper DITHER must be on.
P5 Integral Gain  Changes integral gain if jumper I is on. Turn CW to increase gain. Adjust for system stability.
P6 Filter Frequency  Changes corner frequency of low-pass filter on differentiator. Turn CW to increase frequency. Adjust to reduce excessive noise.
P7 Trim  Changes authority of signal on terminal 7. Turn CW to reduce authority. Adjust to provide scaling of input at terminal 7.
P8 Derivative Gain  Changes derivative gain if jumper D is on. Turn CW to decrease gain. Adjust to add phase lead.
P9 Scale  Changes authority of signal on terminal 9. Turn CW to reduce authority. Adjust to provide scaling of input at terminal 9.
Servoamplifier Schematic

Model NF122-202A1

Typical Applications

Proportional Loops:
- (current drive)
- position, pressure, force, and torque control

Integral Loops:
- (current drive)
- velocity and flow control

Voltage-to-Current Converter:
- to drive servovalve when loop is closed with a digital controller

Voltage Driver for Proportional Valves:
- position, pressure, force, and torque control

Note 1: To energize relay, connect terminal 2 to terminal 24 or connect +5 to +15 Vdc to terminal 1.
Note 2: Place U/J jumper in I position for current drive. Place I/U jumper in U position for voltage drive.
Note 3: Voltage at test point "*Ve" must not exceed ±15 Vdc.
Note 5: • = pin 1 (square pin).

Moog Controls
This Design Series "C" actuator includes improved features to provide greater strength and service life under the most severe conditions.

Standard features of the HTR Series include:

- **TAPERED ROLLER BEARINGS**
  Large tapered roller bearings are used to support the pinion and output shaft, allowing the unit to support high external radial and thrust loads. These bearings ensure a minimum of downtime for high cycling applications, as well as reducing total system complexity.

- **DUCTILE IRON HOUSING**
  A high strength ductile iron housing is now standard on all size actuators. This rugged housing provides greater shock resistance, greater flexibility in mounting, and greater assurance of long unit life.

- **SAE SIDE PORTS**
  SAE side ports are used to provide a compact and leakfree actuator. The side ports can be specified in any one of four orientations to simplify plumbing and installation. SAE straight thread O-ring ports give accurate and tight fluid connections with guaranteed zero external leakage.

- **WEAR-PAK PISTONS AND SEALS**
  High strength steel pistons are piloted to the rack, ensuring concentricity. Filled PTFE wear bands eliminate metal to metal contact and scoring. Self energizing deep Molythane PolyPak seals reduce maintenance with virtually leakproof operation and long life.

- **CHROME ALLOY STEEL PINION AND RACK**
  Through hardened high quality chromium alloy steel is used for the rack and pinion. The through hardening provides maximum shock resistance and strength while minimizing wear, providing long, dependable service life.
Specifications

END CAPS
Machined from cold rolled steel plate, designed to NFPA standard cylinder bore sizes for increased flexibility of options and greater reliability.

TIE RODS
Medium alloy cold worked steel with precision rolled thread for greater strength and fatigue resistance.

BRONZE RACK BEARINGS
A large support area for the rack is provided by a bronze rack bearing, which reduces wear and gives long life. (Note: standard on HTR15 through HTR600.)

RACK & PINION
Heavy duty gear design is made from through hardened chrome alloy steel for maximum strength and shock resistance and long, dependable operation.

HOUSING
High strength ductile iron provides ultimate strength and resistance to shock loads.

KEYWAY
at 12:00 position at mid stroke of actuator.

THREADED MOUNTING HOLES
(4) each side offers choice of mounting surfaces for flexibility in design, optional mounting surfaces also available.

THREADED BEARING RETAINER (FAR SIDE)
assures proper tapered roller bearing preload and resultant bearing load capacity by eliminating the inconvenience and guesswork of shims. Once properly torqued, a set screw securely locks the retainer in place, even under shock and high load conditions.

PISTON SEALS
Heavy duty deep Molythane PolyPak seals are self-compensating for extreme life, zero leakage and reduced maintenance.

STANDARD MALE KEYED SHAFT
is as large as possible to ensure superior strength; pinion and output shaft are one piece to provide long life.

TAPERED ROLLER BEARINGS
provide substantial pinion and shaft support ensuring a rigid and long lasting assembly. The large bearings allow external radial and thrust loads to be applied as well, simplifying complexity and providing longer service life, even under high cycling applications.

PISTON:
one piece is piloted ensuring:
A heavy duty elm to metal, resultant c binding.

NOTE:
All pressure containing seals can be inspected or replaced without removing actuator from customer's shaft or disturbing actuator mounting.

For additional information - call your local Parker Fluidpower Motion & Control Distributor.
HTR Series

The HTR Series actuator incorporates significant features and improvements designed to give superior life under the most severe operating conditions. These features include high capacity tapered roller bearings, chrome alloy steel pinion and racks, and high strength ductile iron housing. The HTR Series is the most rugged and durable tie rod style actuator available today.

The HTR Series actuator will provide superior life on the most demanding applications, including machine tools, plastics and rubber machinery, process equipment, material handling equipment, and in basic metals manufacturing.

The many options available on the HTR Series allows the actuators to be "designed" to the application, which can reduce overall system complexity and cost. For example, the optional hollow shaft and base mount can eliminate the need for external support bearings, as the actuator bearings themselves have additional load capacity.

Or, specifying the optional cushions can eliminate the need for external deceleration devices, and reduce system shock and vibration.

The HTR Series actuator is also designed for ease of maintenance. The Wear-Pak pistons with self-energizing Molythane PolyPak piston seals can be inspected or serviced without removing the actuator from the mounting or shaft. The piston seals are the only dynamic seals that are pressurized, the pinion and shaft seals never see system pressure, eliminating the possibility of external leakage.

To guarantee delivery of only the highest quality products, all HTR Series actuators are 100% inspected and tested before shipment. These tests include a static proof test at 4500 psi, a breakaway pressure test, and a rigorous inspection to detect any external leakage, all ensuring shipment of the finest rotary actuator possible.

HTR SERIES SPECIFICATIONS

<table>
<thead>
<tr>
<th>Specification</th>
<th>HTR22/45</th>
<th>HTR40</th>
<th>HTR75</th>
<th>HTR100</th>
<th>HTR300</th>
</tr>
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<tbody>
<tr>
<td>Maximum Operating Pressure</td>
<td>3000 psi non-shock</td>
<td>2000 psi non-shock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proof Pressure</td>
<td>4500 psi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Rotations</td>
<td>90°, 180°, 360°</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Rotational Tolerance</td>
<td>-0°, +2°</td>
<td></td>
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<tr>
<td>Output Torques</td>
<td>900 lb-in to 600,000 lb-in</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Leakage - External</td>
<td>0 cubic inches per minute</td>
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<tr>
<td>Leakage - Internal</td>
<td>0 cubic inches per minute</td>
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<td>Maximum Breakaway Pressure</td>
<td>75 psi</td>
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<td>Operating Temperature (Standard Nitrile Seals)</td>
<td>-40°F to 180°F</td>
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<td>Mounting Orientation</td>
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<tr>
<td>Timing</td>
<td>Keyway located at 12:00 position at midstroke of actuator</td>
<td></td>
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</table>

SPECIFICATION TABLE

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Automation Actuator Division
Wadsworth, OH 44281
### Dimensional Data

**HTR.9 thru HTR10**

**SINGLE AND DOUBLE RACK WITH FACE MOUNT (A) AND MALE KEYED SHAFT (B)**

<table>
<thead>
<tr>
<th>Model</th>
<th>Rotation Degrees</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
<th>N</th>
<th>O</th>
<th>P</th>
<th>R</th>
<th>S</th>
<th>T</th>
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<td>2.375</td>
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<td>1/16 - 18 x 1/2 DP</td>
<td>.875</td>
<td>.874</td>
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<td>1.188</td>
<td>1/16 - 18 x 1/2 DP</td>
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<td>1/2</td>
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<td>1</td>
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<td>.72</td>
<td>1/16 - 18 (#6)</td>
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<td>1.188</td>
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<td>.72</td>
<td>1/16 - 18 (#6)</td>
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**HTR15 thru HTR600**

**SINGLE AND DOUBLE RACK WITH FACE MOUNT (A) AND MALE KEYED SHAFT (B)**

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<th>C</th>
<th>D</th>
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<th>O</th>
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<th>R</th>
<th>S</th>
<th>T</th>
<th>U (SAE)</th>
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<tbody>
<tr>
<td>HTR75</td>
<td>360</td>
<td>32/4</td>
<td>8</td>
<td>6/4</td>
<td>7</td>
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<td>1/16 - 18 x 1/2 DP</td>
<td>2.999</td>
<td>.750</td>
<td>2.577</td>
<td>3/4</td>
<td>1/8</td>
<td>.84</td>
<td>1/16 - 18 (#12)</td>
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For additional information – call your local
## MOUNTING OPTIONS (B, P)

### Base Mounting (B)

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<tr>
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<td>2.250</td>
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<td>1.613</td>
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<td>3½</td>
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<td>1.613</td>
<td>.719</td>
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<tr>
<td>HTR3.7</td>
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<td>3¾/16</td>
<td>2.625</td>
<td>3.000</td>
<td>4</td>
<td>7/16-18 NC x 1/2 DP</td>
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<tr>
<td>HTR7.5</td>
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<td>3¾/16</td>
<td>3.000</td>
<td>3.000</td>
<td>4</td>
<td>7/16-18 NC x 1/2 DP</td>
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<td>HTR5</td>
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<td>3¾/16</td>
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### Pilot Mounting (P)

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<td>2.673</td>
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<td>HTR22/45</td>
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<td>HTR600</td>
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## Shaft Options

All shaft options shown in mid-stroke position.

### Female Keyed (A)

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<td>7/16-18 NC x 1/2 DP</td>
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<tr>
<td>HTR3.7</td>
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<td>7/16-18 NC x 1/2 DP</td>
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<tr>
<td>HTR7.5</td>
<td>1.613</td>
<td>2.625</td>
<td>3½</td>
<td>7/16-18 NC x 1/2 DP</td>
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</tr>
<tr>
<td>HTR5</td>
<td>1.613</td>
<td>2.625</td>
<td>3½</td>
<td>7/16-18 NC x 1/2 DP</td>
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<tr>
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### Female SAE 10B Spline (D)

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### Male SAE 10B Spline (E)

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<td>7/16</td>
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<td>.872</td>
<td>.133</td>
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<td>7/16</td>
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<td>1³/16</td>
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<td>.775</td>
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## Seals (V, W)

A durable Wear-Pak piston is standard on all units. This includes a deep Molythane PolyPak seal to eliminate leakage, and a filled PTFE wear ring to prevent metal to metal contact, wear, and contamination damage.

### Operating Temperature Limits: -40°F to 180°F

Recommended For: General purpose, petroleum based fluids.

Filtration Requirements: ISO class 17/14 cleanliness level.

Optional seals:

- **(V) Viton**
  - Recommended for: High temperature and/or synthetic fluids.
  - Operating Temperature Limits: -20°F to 400°F

- **(W) Carboxylated Nitrile** (Piston seals only)
  - Recommended for: Water glycol and high water content fluids.
  - Operating Temperature Limits: 50°F to 180°F
**Options**

**PORT SIZE & LOCATION**

![Port Size & Location Diagram]

**NOTE:**
1. Port position 1 is standard.
2. Port position 2, 3 and 4 are standard options available at no additional cost.
3. Port position 5 is available at additional cost.

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<th>Model</th>
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<th>NPT (2)</th>
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</thead>
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<td>1/8-18 (SAE 6)</td>
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<tr>
<td>HTR3.7</td>
<td>1/8-18 (SAE 6)</td>
<td>1/4</td>
</tr>
<tr>
<td>HTR7.5</td>
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</tr>
<tr>
<td>HTR5</td>
<td>1/8-18 (SAE 6)</td>
<td>1/4</td>
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<tr>
<td>HTR10</td>
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<table>
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<th>Standard SAE Straight Thread (1)</th>
<th>NPT</th>
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<td>HTR30/45</td>
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<td>HTR75</td>
<td>1/2-20 (SAE 12)</td>
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<td>HTR300</td>
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<td>HTR600</td>
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</tbody>
</table>

**CUSHIONS (1, 2, 3, 4)**

The standard cushion operates over the last 20° of rotation in either or both directions. A floating bushing ensures no binding of cushion spear. For severe operating conditions high performance cushions should be fitted on double rack units. All cushions are fully adjustable. On double rack units with only 2 cushions, cushions are located on upper cylinders.

<table>
<thead>
<tr>
<th>Port Position</th>
<th>Cushion Position</th>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
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<tr>
<td>4*</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
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*Single rack only.

**HIGH PERFORMANCE CUSHION (8)**

(This option can be specified on double rack units only)

By combining the output/exhaust flow from two cylinders, then routing it through a single cushion bushing and cushion adjuster, cushion performance is enhanced. The increased cushion flow results in better control, doubles the cushioning torque, and eliminates dangerous pressure intensification.

This unique circuit also eliminates two pipe or tubing tees.

**OPERATION:**

The work ports of a standard directional valve are plumbed to ports C-1 and C-2. Port A-1 is plumbed directly to A-2, and port B-1 is plumbed to B-2. When pressure is applied to port C-1 (clockwise shaft rotation), fluid is also directed through line A to the other rack. Exhaust flow from B-1 through B-2 is directed through the cushion bushing and cushion adjust ment. When the cushion spear closes off the main passage, total flow from both end caps is directed across one cushion adjustment needle, equalizing back pressure and improving performance. Alternatively, pressurizing C-2 and exhausting C-1 reverses the operation.

**DIMENSIONAL INFORMATION:**

Units are identical to standard double rack and pinion units, with the exception of porting location. This chart describes the location of the ports.

For additional information – call your local Parker Fluidpower Motion & Control Distributor.
STROKE ADJUSTERS, 5° and 30°

NOTE:
1. Maximum unit rotation is equal to rotation specified in model code. Adjusters allow rotational positioning equal to or less than the maximum rotation.
2. 5° stroke adjusters are available with or without cushions. Double rack units will have cushions on upper rack and stroke adjusters on lower rack. Single rack units will require additional "A" length.
3. 30° stroke adjusters not available with cushions.

<table>
<thead>
<tr>
<th>Model</th>
<th>(1) Turn Adj.</th>
<th>5° Adjustment w/o Cushioned End Cap</th>
<th>5° Adjustment w/ Cushioned End Cap</th>
<th>30° Adjustment w/o Cushioned End Cap</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTR.9</td>
<td>4.0°</td>
<td>0.50</td>
<td>0.88</td>
<td>0.75</td>
<td>5/16</td>
<td>5/16 - 24 UNF</td>
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<tr>
<td>HTR1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5/16</td>
<td>5/16 - 24 UNF</td>
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<tr>
<td>HTR3.7</td>
<td>3.3°</td>
<td>0.63</td>
<td>1.13</td>
<td>1.13</td>
<td>1/4</td>
<td>1/4 - 20 UNF</td>
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<tr>
<td>HTR7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/4</td>
<td>1/4 - 20 UNF</td>
</tr>
<tr>
<td>HTR10</td>
<td>2.5°</td>
<td>0.63</td>
<td>1.13</td>
<td>1.13</td>
<td>3/8</td>
<td>3/8 - 16 UNF</td>
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<tr>
<td>HTR15/22</td>
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<td>0.88</td>
<td>1.81</td>
<td>1.63</td>
<td>3/8</td>
<td>3/8 - 16 UNF</td>
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<tr>
<td>HTR30/45</td>
<td></td>
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<tr>
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<td>2.0°</td>
<td>2.56</td>
<td>3.75</td>
<td>3.56</td>
<td>1/2</td>
<td>1/2 - 12 UNF</td>
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<tr>
<td>HTR150</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/2</td>
<td>1/2 - 12 UNF</td>
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<tr>
<td>HTR300</td>
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<td>3.56</td>
<td>6.06</td>
<td>5.31</td>
<td>2 1/2</td>
<td>1/2 - 12 UNF</td>
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<tr>
<td>HTR600</td>
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BEARING LOAD CAPACITIES

<table>
<thead>
<tr>
<th>Model</th>
<th>Radial Load (lbs.)</th>
<th>Thrust Load (lbs.)</th>
<th>Overhang Moment (lb-in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>R (Per Bearing)</td>
<td>R (Per Bearing)</td>
<td>R x A</td>
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<tr>
<td>----------</td>
<td>-------------------</td>
<td>-------------------</td>
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<tr>
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<tr>
<td>HTR10</td>
<td>7,670</td>
<td>6,790</td>
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<td>HTR15</td>
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<tr>
<td>HTR22</td>
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<tr>
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<tr>
<td>HTR600</td>
<td>43,150</td>
<td>43,150</td>
<td>43,150</td>
</tr>
</tbody>
</table>

NOTE:
1. Static Bearing Load Capacities = Dynamic Values x 1.5
2. Values listed are "Bearing" moment capacities. Standard male shaft sizes do not provide 4:1 design factor at these operating conditions. Larger shaft sizes are available. Consult factory for further details.
PROXIMITY SWITCHES

The inductive type proximity switch provides end of rotation indication. The non-contact probe senses the presence of the ferrous cushion spear and has no springs, plungers, cams or dynamic seals that can wear out or go out of adjustment. The switch is solid state and meets NEMA 1, 12 & 13 specifications. For ease of wiring the connector housing is rotatable through 360°. To rotate, lift the cover latch, position, and release.

The standard proximity switch controls 20-230 VAC/DC loads from 5 to 500 mA. The low 1.7 mA off-state leakage current can allow use for direct PLC input. The standard short circuit protection (SCP) protects the switch from a short in the load or line upon sensing such a condition (5 amp or greater current) by assuming a non-conductive mode. The fault condition must be corrected and the power removed to reset the switch preventing automatic restarts.

The low voltage DC switch is also available for use with 10-30 VDC. This switch is in a non-rotatable housing, but does incorporate the short circuit protection.

Both switches are equipped with two LEDs, "Ready" and "Target". The "Ready" LED is lit when power is applied and the cushion spear is not present. The "Target" LED will light and the "Ready" LED will go out when the switch is closed, indicating the presence of the cushion spear. Both LEDs flashing indicates a short circuit condition.

NOTES:
1. Available with or without cushions.
2. Not available with stroke adjusters.
3. Pressure rating: 1500 psi
4. Operating temperature: -4°F to 158°F
5. Specify switch type, orientation and voltage when ordering.
6. The low voltage DC switch is available in non-rotatable style only, consult representative for further information.

HIGH VOLTAGE SWITCH (20-230 VAC/DC)

<table>
<thead>
<tr>
<th>AC White (1)</th>
<th>Pin Receptacle Color Code</th>
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<tbody>
<tr>
<td>SW OL.1</td>
<td>1. Green</td>
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<tr>
<td>OL.2</td>
<td>2. Black</td>
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<tr>
<td>Black (2)</td>
<td>3. White</td>
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</tbody>
</table>

Internally Short Circuit Protected Brad Harrison 49599 Connector

LOW VOLTAGE DC SWITCH (10-30 VDC)

<table>
<thead>
<tr>
<th>DC White (1)</th>
<th>Pin Receptacle Color Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW Orange (4)</td>
<td>1. White: +10 to 30 VDC</td>
</tr>
<tr>
<td>Black (5)</td>
<td>2. Red: Source</td>
</tr>
<tr>
<td>Red (2)</td>
<td>3. Ground Not Connected, Nor Required (Green)</td>
</tr>
</tbody>
</table>

4. Orange: Sink 5. Black Common Brad Harrison 41310 Connector

NOTES:
For additional information – call your local Parker Fluidpower Motion & Control Distributor.
APPLICATION:
The potentiometer option is an analog feedback device designed for use on a wide variety of applications that utilize closed-loop feedback to achieve accurate position, velocity, or motion control. The potentiometer option can also be used on open-loop systems as a continuous, infinite position monitoring device.

OPERATION:
A potentiometer is a variable resistor. There are three electrical terminals on the potentiometer - two on opposite ends of a fixed conductive plastic element (terminals 1 and 3, see electrical schematic on the right) and one attached to the "wiper" that moves along the conductive element as the shaft rotates (terminal 2). As the potentiometer shaft rotates, resistance between terminal 2 and terminals 1 and 3 charges.

Because the resistance of the potentiometer is linear (± 0.1%), when a fixed voltage level is supplied across terminals 1 and 3, shaft position can be determined by reading the output voltage at terminal 2. By measuring the rate of change in voltage at terminal 2, rotational velocity can be determined. To determine actuator position or velocity, the potentiometer shaft is connected to the actuator shaft via a flexible coupling. The potentiometer is enclosed in a water tight enclosure for resistance to dirty environments.

ORDERING INFORMATION:
Consult the factory or your local representative for specific application and ordering information.

POTENTIOMETER SPECIFICATIONS:
- Potentiometer: 7/8" diameter single turn precision servo-mount with conductive plastic element
  10K ohms
- Resistance: ± 10%
- Resistance Tolerance: ± 1%
- Linearity: Essentially infinite
- Resolution: ±1%
- Effective electrical angle: 340° ± 3%
- Power rating: 70°C - 1 watt
  125°C - 0 watt
- Temperature Rating: ±1°C to +125°C
- Backlash: 0.1° max.
- Rotational life: 20,000,000 rev.
  Rear, turret style
- Available on:
  PTR/LTR Series
  HTR Series
  M Series
  Vane - Standard Series

- Electrical Schematic:

NOTE:
1. Rack and pinion actuators have a small amount of backlash-consider before applying.
2. Electrohydraulic options and operation may affect other actuator components such as seals, bearings, etc. Consult your local representative for additional information.
**APPLICATION:**
The resolver option is a precision analog feedback device designed for use on a wide variety of applications that utilize closed-loop feedback to achieve accurate position, velocity, or motion control. The resolver option can also be used on open-loop systems as a continuous, infinite position monitoring device.

**OPERATION:**
A resolver is a brushless rotary synchronous transformer which eliminates wiping contact and provides higher response and accuracy. A voltage and frequency is applied across the primary coil; changes in shaft position cause a proportional change in the secondary winding. Measuring the rate of change also provides velocity. To determine actuator position or velocity, the potentiometer shaft is connected to the actuator shaft via a flexible coupling. The potentiometer is enclosed in a watertight enclosure for resistance to dirty environments.

**ORDERING INFORMATION:**
Actuators can be supplied as complete packages, or with an enclosure for the mounting of a customer supplied resolver. Consult the factory or your local representative for specific application and ordering information.

**RESOLVER SPECIFICATIONS:**
- Resolver: 11D servo-mount, brushless synchro
- Input Voltage: 7.5 volts
- Input Frequency: 4000 Hz
- Input Current: 13.5 mA (max)
- Input Power: 60 mW
- Output Voltage: 4 volts
- Phase Shift: 0
- Sensitivity: 70 mV/°
- DC Rotor Resistance: 8 ohms
- DC Stator Resistance: 19 ohms
- Total Null Voltage: 10 mV
- Accuracy (Maximum error): 7 minutes*
- Leads: #28 AWG, 12 inches long
- Available on: PTR/LTR Series, HTR Series, M Series
- Vane - Standard Series

**NOTE:**
1. Rack and pinion actuators have a small amount of backlash - consider before applying.
2. Electrohydraulic options and operation may affect other actuator components such as seals, bearings, etc. Consult your local representative for additional information.

For additional information – call your local Parker Fluidpower Motion & Control Distributor.
HTR Series
Special Option

LINEAR POTENTIOMETER FEEDBACK PACKAGE

APPLICATION:
The linear potentiometer option is an analog feedback device typically used for rotary actuator rotations exceeding 340°, or where a standard rotary potentiometer cannot be connected to the actuator shaft. Applications for this device include closed loop feedback to achieve accurate position, velocity, or motion control. This option can also be used on open-loop systems as continuous, infinite position monitoring device.

OPERATION:
A potentiometer is a variable resistor. There are three electrical terminals on the potentiometer - two on opposite ends of a fixed conductive plastic element (terminals 1 and 3, see electrical schematic on the right) and one attached to the "wiper" that moves along the conductive element with the piston and rack. As the wiper moves along the element, resistance between terminal 2 and terminals 1 and 3 charges.

Because the resistance of the potentiometer is linear (± .1%), when a fixed voltage level is supplied across terminals 1 and 3, shaft position can be determined by reading the output voltage at terminal 2. By measuring the rate of change in voltage at terminal 2, rotational velocity can be determined. Since the linear potentiometer is enclosed in the actuator itself, it is safe for operation in dirty or wet environments.

ORDERING INFORMATION:
Consult the factory or your local representative for specific application and ordering information.

LINEAR POTENTIOMETER SPECIFICATIONS:
- Potentiometer: Calibrated conductive film with low resistance wiper carnage.
- Resistance: Approx. 1 K ohm per inch of stroke
- Resistance Tolerance: ± 20%
- Linearity: 0.1% of full stroke
- Voltage: 5 - 50vdc
- Resolution: Essentially infinite*
- Repeatability: 0.001*
- Power rating:
  - 70°C - 1 watt/cm²
  - 125°C - 0 watt/cm²
- Temperature Rating: -55°C to 125°C
- Pressure Rating: 3,000 psi
- Terminal: 3 pin micro connector
- Available on:
  - Rack & Pinion* - PTR/LTR Series
  - HTR Series
  - M Series
- Electrical Schematic:

NOTE:
1. Rack and pinion actuators have a small amount of backlash—consider before applying.
2. Electrohydraulic options and operation may affect other actuator components such as seals, bearings, etc. Consult your local representative for additional information.

Automation Actuator Division
Wadsworth, OH 44281
APPLICATION:
The linear displacement transducer (LDT) option provides digital feedback of the rack position via interaction between two magnetic fields. The LDT option is recommended for applications where rotation exceeds 340°, or where a standard rotary potentiometer or resolver cannot be connected to the actuator output shaft. Applications for this device include closed loop feedback to achieve accurate position, velocity, or motion control. This option can also be used on open-loop systems as a continuous, infinite position monitoring device.

OPERATION:
The LDT utilizes two magnets, a permanent one located on the piston, the other is a magnetic pulse generated by a current pulse along a wire inside a waveguide tube. The interaction between the fields produces a strain pulse which travels down the waveguide tube and is sensed by a coil at the end of the device. Position and velocity of the permanent magnet is pinpointed by measuring the lapsed time between the launching of the current pulse and the arrival of the strain pulse. An interface box converts this information to a usable output form, either digital or analog.

ORDERING INFORMATION:
Actuators can be provided as complete packages or with drilling and mounting for customers purchased LDTs. Consult the factory or your local representative for specific application and ordering information.

LDT SPECIFICATIONS:
- Linearity: ±.05% of full stroke (min. ±.002 in.)
- Repeatability: ±.0001 in.*
- Temperature Coefficient (probe): <10 ppm/°F
- Temperature Coefficient (electronics box):
  - Digital: <10 ppm/°F
  - Analog: 55 ppm/°F
- Resolution*:
  - Digital: .004, .002, .001 or .0005 available
  - Analog: Stepless continuous output*
- Output: Digital: Absolute, TTL compatible, parallel or serial
  - Analog: -10 to +10 Vdc and 20mA range
- Operating Temperature:
  - Digital: 0° to 150°F
  - Analog: 35° to 150°F
- Hysteresis: .0008 in.*
- Available on:
  - Rack & Pinion*: HTR Series
  - M Series

NOTE:
1. Rack and pinion actuators have a small amount of backlash consider before applying.
2. Electrohydraulic options and operation may affect other actuator components such as seals, bearings, etc.
Consult your local representative for additional information.

For additional information – call your local Parker Fluidpower Motion & Control Distributor.
**R Series**

**Ordering Information**

**HTR150-1803-AB11V-C23**

### Heavy Duty Hydraulic Tie Rod Series

- Output in 1000 lb-in at 3000 psi
  - Single Rack Units
    - 9 = 900 lb-in
    - 3.7 = 3,700 lb-in
    - 5 = 5,000 lb-in
    - 15 = 15,000 lb-in
    - 12 = 15,000 lb-in*
    - 75 = 75,000 lb-in
    - 30 = 300,000 lb-in
  - Double Rack Units
    - 3.7 = 3,700 lb-in
    - 7.5 = 7,500 lb-in
    - 10 = 10,000 lb-in
    - 30 = 30,000 lb-in
    - 45 = 30,000 lb-in*
    - 150 = 150,000 lb-in
    - 600 = 600,000 lb-in

### Degrees Rotation

- 90°
- 180°
- Specify Other Rotations

### Bushing

- None (STD)
- CW Rotation**
- CCW Rotation**
- Both Rotations
- Four Cushions***
- High Performance Cushion***
- Special

### Stroke Adjusters (see Stroke Adjuster Table)

- None
- 0-30° CW Rotation
- 0-30° CCW Rotation
- 0-30° Both Rotations
- 0-5° Both Rotation*

### Mounting Style

- Face (STD)
- Base Mount
- Pilot Mount

### Shaft Configuration

- Female Keyed
- Single Male Keyed (STD)
- Double Male Keyed
- Female 10B Spline
- Single Male 10B Spline
- Double Male 10B Spline
- SAE Straight Thread (STD)
- NPTF
- 3 - Flange
- 4 - Side: Position 4
- 5 - End
- 6 - Special

### Seals

- Molythane/Nitrile (STD)
- Viton
- Carboxilated Nitrile

### Special Options (Detail in Clear Text)

- Proximity Switches
- Feedback Potentiometer

### Special Actuator Code

- Proximity Switches
- Feedback Potentiometer

### Design Series

- Assigned by Factory

---

* HTR 22/45 rated to 2000 psi maximum
** Viewed from Shaft End
*** Double Rack Models Only. Use four cushions for existing applications only. For new applications, use option 8, High Performance Cushion. See options section for additional information.
* Not available with End Ports. Standard 5° Stroke Adjusters and Standard Cushions available together on all units.
* Single rack units required additional "A" length.
* Not Available with End Ports or Cushions

- Automation Actuator Division
- Wadsworth, OH 44281

- Parker
- Motion & Control
Parker Series EH Electrohydraulic Actuator

Parker EH-IR Actuator
The Ultimate in Accurate, Dependable Linear Position

Here's How The Parker EH-IR Feeds Back Linear Position

The precision helical screw nut is attached to the cylinder piston. As the piston moves through its stroke, the nut "backs-drives" the helical screw, rotating the screw within a set of precision thrust and radial bearings. The helical screw shaft is attached to the shaft of a rotary encoder with a flexible coupling. The linear motion of the cylinder piston is converted to rotary motion by the precision helical screw.

Standard Specifications and Features Include:

- Max. non-linearity (scale dependent) of .0001/inch
- Repeatability to ±0.005"
- Rotary output is one revolution per inch of stroke
- Mounting adapters to accept most rotary encoders, resolvers are available to provide an absolute or incremental feedback
- Complete factory testing of assembled unit-test report provided
- Unit flushed and certified to NAS-1638 particulate count Class 4
- Proven machine tool technology adapted to NFPA hydraulic cylinders for optimum performance and life
- Straight thread 'O'ring ports for "no leak" pressure and return hydraulic connections
- Encoder connector varies with the encoder order
- TTL compatible quadrature output is standard for position and velocity feedback
- Stroke length up to 48 inches
- Consult factory on velocities exceeding 20 inches per second

Regional Plants
- Santa Fe Springs, CA 219/297-3182
- Plymouth, MI 313/455-1700
- Hillsborough, NC 919/732-9571
- Portland, OR 503/265-8150
- San Diego, CA 619/448-2222
- Toronto, Ont. Can. 416/253-4567
- Nantes, France 33/49-72-52-60
- Lachute, Quebec, Can. 514/371-8288
Cap Fixed Eye
Parker Style B with CLP Feedback Only

Cap Fixed Clevis
Parker Style BB with CLP Feedback Only

Cap Spherical Bearing
Parker Style SB with CLP Feedback only

Pressure rating is for maximum life of cylinder and bearing based on dynamic load of commercial bearing.

Rod End Dimensions — See Table 2

"Special" THREAD STYLE 3
Special thread, extension, rod eye, blank, etc., are also available.
To order, specify "Style 3" and give desired dimensions for CC or KK, A and LA. If otherwise special, furnish dimensioned sketch. For female threads, see page 152.

For additional information – call your local Parker Fluidpower Motion & Control Distributor.
## Parker Series EH Electrohydraulic Actuator

### Table 1 — Envelope and Mounting Dimensions

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<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1.751</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>%</td>
<td>7%</td>
<td>2%</td>
</tr>
<tr>
<td>6</td>
<td>7%</td>
<td>#16</td>
<td>%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>2.001</td>
<td>1%</td>
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<td>1%</td>
<td>1%</td>
<td>%</td>
<td>7%</td>
<td>2%</td>
</tr>
<tr>
<td>7</td>
<td>8%</td>
<td>#16</td>
<td>%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
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<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>2.501</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>%</td>
<td>7%</td>
<td>2%</td>
</tr>
<tr>
<td>8</td>
<td>9%</td>
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<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>3.001</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>%</td>
<td>7%</td>
<td>2%</td>
</tr>
</tbody>
</table>

* Dimension CD is pin diameter.
* For lower flow servo valves — see page 153, Group A, B, C, G.
* ** For higher flow servo valves — see page 153, Group D, E, F, H. Velocity of CLP actuators must not exceed 40 ips.

### Table 2 — Rod End and Envelope Dimensions

<table>
<thead>
<tr>
<th>BORE</th>
<th>ROD NO</th>
<th>ROD DIA.</th>
<th>THREAD</th>
<th>+000</th>
<th>C</th>
<th>D</th>
<th>LA</th>
<th>NA</th>
<th>V</th>
<th>W</th>
<th>XD</th>
<th>ZD</th>
<th>ZH</th>
</tr>
</thead>
</table>

Note: Electrical port or connector will be provided at position 1 of rear cap.
760 Series Servovalves

The 760 Series is a high performance, two-stage design that covers the range of rated flows from 1 to 15 gpm at 1000 psi valve drop. The output stage is a closed center, four-way, sliding spool. The pilot stage is a symmetrical double-nozzle and flapper, driven by a double air gap, dry torque motor. Mechanical feedback of spool position is provided by a cantilever spring. The valve design is simple and rugged for dependable, long life operation.

Specifications:

Fluid Supply: 760 Series Servovalves are intended to operate with constant supply pressure.

| Supply Pressure: | Minimum: 200 psi (14 bar)  |
|                 | Maximum Standard: 3500 psi (245 bar) |
|                 | Maximum (special order): 5000 psi (350 bar) |

Pressure: 150% of supply pressure at P port
100% of supply pressure at R port

Fluid: Compatible with common hydraulic fluids
Recommended viscosity range: 60-450 SUS @ 100°F (10-97 cSt @ 38°C)

Cleanliness Level: ISO DIS 4406 code 16/13 max. 14/11 recommended

Operating Temperature:
Minimum: -40°F (-40°C) (maximum fluid viscosity: 6000 SUS)
Maximum: +275°F (+135°C)

Rated Flow Tolerance: ±10%

Symmetry: < 10%
Hysteresis: < 3%
Threshold: < 1/2%

Null Shift:
with temperature, 100°F variation: < 2%
with acceleration to 10g: < 2%
with supply pressure 1000 psi change: < 2%
with back pressure 0 to 500 psi: < 2%

Frequency Response: Typical response characteristics for 760 Series Servovalves are shown in Figures 1, 2, and 3.

Step Response: Typical transient responses of 760 Series Servovalves are shown in Figure 4. The straight line portion of the response represents saturation flow from the pilot stage which will increase with higher supply pressures.
**Quotation # 1212**

**TO**  
MARTIN MARIETTA ENERGY SYSTEMS  
ROBOTICS & PROCESS CONTROL  
OAK RIDGE, TN 37830  
ATTN: BRETT KARBAS

**REF. NUMBER**

**DATE OF QUOTE**  6-13-95

**EXPIRATION OF QUOTE**

**F.O.B.**  
SHIPPING POINT

**QUANTITY** | **MATERIAL DESCRIPTION** | **PRICE**
--- | --- | ---
1 | PARKER HYDRAULIC CYLINDER MODEL 2"TD2EKT513A X 55"  
2" BORE  1" ROD  
HIGH LOAD PISTON  
7" STOP TUBE  
LOW FRICTION ROD GLAND  
BOLT ON MANIFOLD FOR MOOG 760 PARKER GROUP A  
HEAD END PLUMBED TO CAP  
LA = 28"  
A = 1 1/8"  
KK = 3/4-16 MALE | $1167.80 EA.

1 | PARKER HYDRAULIC CYLINDER MODEL 2"TD2HKT523A X 55"  
2" BORE  1 3/8" ROD  
HIGH LOAD PISTON  
7" STOP TUBE  
LOW FRICTION ROD GLAND  
BOLT ON MANIFOLD FOR MOOG 760 PARKER GROUP A  
HEAD END PLUMBED TO CAP  
LA = 28"  
A = 1 5/8"  
KK = 1-14 MALE  
LDT WITH APM - 10VDC TO + VDC POSITION ONLY | 3537.20 EA.

1 | BALUFF LINEAR DISPLACEMENT TRANSDUCER  
MODEL BTX-2-G21-1270-X-550  
BK-S50-05 CONNECTOR WITH 15 FT. CABLE | 781.00 EA.

1 | CYLINDER WITH TRANSDUCER  
5 - 6 WEEKS | 
TRANSDUCER 3 - 10 DAYS | 
SHIPPING PROMISE

**HoYT N. PAYNE COMPANY**

**JACK CAMPBELL**

1. This and other information from Hoyt N. Payne Co. Provide product or system options for further investigation by users having technical expertise before you select or use any product or system. It is important that you analyze all aspects of your application and review the information concerning the product in the current product catalog. The user, through its own analysis and testing, is solely responsible for making the final selection of the system and components and assuring that all performance safety and warning requirements of the application are met.

2. This quotation is made subject to the terms and conditions listed herein and the standard terms and conditions of the suppliers of the materials quoted. Copies available on request.

3. Seller's liability with respect to any item not of seller's manufacture shall be limited to that of the vendor thereof.

4. Unless otherwise specified, prices quoted herein are subject to revision to the prices which are in effect at the time shipment is made.

5. If an order is received for the items quoted herein, it will not be subject to cancellation without indemnifying both the suppliers of the materials quoted and the Hoyt N. Payne Co. against loss.

6. Unless specifically stated otherwise, in no event shall seller be liable here under or otherwise for loss of profits, special, incidental or consequential damages.
Balluff magnetostrictive linear displacement transducers offer non-contact, wearfree, and accurate linear positioning. They are designed for rugged industrial environments wherever linear motion must be controlled.

Balluff offers three housing configurations to suit most any application. The captive and floating magnet profile housings are designed to the same formats as linear potentiometers. The rod style is designed for hydraulic cylinder positioning or external mounting.

Linear stroke lengths range from 50 to 3606mm (2 in. to 142 in.).

Available output signals range from analog DC voltage or current to pulse signal timing.

All BTL-2 transducers contain integrated surface mount electronics designed for high reliability and accuracy.

**Principles of Operation**

Although variously referred to as an "LVDT", an "LDI", or even a "pot", the accurate term for the Balluff BTL is a "magnetostrictive transducer."

Magnetostriction, a physical effect first identified by the 19th century British physicist J.P. Joule, is defined as the cross-sectional and longitudinal deformation of a ferromagnetic material in the presence of a defined magnetic field. This property has been exploited in apparatus for generating ultrasound as well as devices for measuring quickly changing forces, such as strain gauges.

In the BTL, the magnetostrictive element is an extremely small diameter (i.d. <0.012") Ni-Fe alloy tube held in place inside a protective outer tube. This so-called waveguide runs the length of the transducer. To initiate a measurement for position update, a circuit in the housing pulses a current on a conductor wire which has been threaded coaxially through the waveguide. During the short time that this pulse is on, a rotating electromagnetic field surrounds the waveguide. At the same time, lines of field from magnets in the marker ring or block which has been attached externally to the moving member of the user's equipment come to focus on the waveguide. The effect of these two fields is to generate a magnetostrictive strain wave just below the magnets, which ripples back down the waveguide to a receiver in the transducer head. This mechanical pulse is converted into an electrical signal through a Balluff patented process. A high-speed clock or an Integrator measures the time between launching of the current pulse and arrival of the torsional wave. Since the velocity of the torsion pulse (typ. 2850 m/s or 8.9 ft/ln.) is known as a material constant, and time has been determined by the clock or Integrator, we now know distance. In essence, a sonic (or ultrasound) delay line has been created which allows us to know the position of the magnet ring to a resolution of 2.5 jim (0.0001") depending on output signal type and stroke length. The user may specify an already scaled analog output signal, or just the raw timing pulses for processing the the controller.
2.3 Spring Loading or Tensioning

The transducer rod (flexible or rigid) can be spring loaded or tensioned using a stationary weight. Attach a spring mechanism or weight to the dead zone of the transducer rod with a clamping device which will not deform the transducer rod. The maximum weight or spring tension is 5 to 7 lbs.

2.4 Cylinder Installation

Figure 2-8 shows a typical cylinder installation. Review the following before attempting this type of installation.

- Use a non-ferrous (plastic, brass, Teflon®, etc.) spacer [1] to provide 1/8 inch (32 mm) minimum space between the magnet and the piston.

- An O-ring groove [2] is provided at the base of the transducer hex head for pressure sealing. MTS uses mil-standard MS33514 for the O-ring groove. Refer to mil-standard MS33649 or SAE J514 for machining of mating surfaces.

- The null space [3] is specified according to the installation design and cylinder dimensions. The analog output module provides a null adjustment. Make sure that the magnet can be mounted at the proper null position.

- The piston head [4] shown is typical. For some installations, depending on the clearances, it may be desired to countersink the magnet.
Highest Standards of Quality through Modern Manufacturing and Testing

The entire signal processing circuitry of the BTL Linear Displacement Transducer uses SMD technology on printed circuit boards.

The actual waveguide is shock mounted.

In the rod style the outer tube and the mounting flange are laser welded, and the stainless steel outer tube is rated to 8,700 PSI (600 bar).

Each and every BTL Linear Displacement Transducer undergoes a strict testing procedure after final assembly.

The following criteria are checked by the computer control:
- temperature characteristics
- temperature cycles from -20°C to +60°C
- short circuit protection of the output drivers
- linearity of the output signal
- polarity reversal protection of the supply voltage
- overvoltage protection to 40 V
- dielectric strength between electronics and housing of 1 kV

The Advantages

Non-contact, reliable linear positioning
IP 67 and NEMA 6 Industrial rated
Rod version rated to 600 bar (8700 PSI)
Various outputs - analog/pulse signals
Interface cards for various signal processing

Full Line of Accessories Available

- Floats
- Connectors
- Special Magnets
- Custom Mounts
- Special connectors/cables
(see pages G42 - G48 for details)
**Linear Displacement Transducer Series BTL-2**

### Housing Styles

- **BTL-2...F**
  - Captive Magnet Housing

- **BTL-2...P**
  - Floating Magnet Housing

- **BTL-2...Z**
  - Rod Style Housing

### System Design

Balluff offers three BTL-2 housing configurations to suit most any application. All three housings can output any of the four analog signals shown. Internal SMT electronics convert absolute magnet positions to voltage or current output signals. Simple interfacing to many controls.

### Analog Output Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Signal Range</th>
<th>Resolution</th>
<th>Total Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0...10 V</td>
<td>0.1 mV</td>
<td>100,000</td>
</tr>
<tr>
<td>B</td>
<td>+5...-5 V</td>
<td>0.1 mV</td>
<td>100,000</td>
</tr>
<tr>
<td>C</td>
<td>-10...+10 V</td>
<td>0.1 mV</td>
<td>100,000</td>
</tr>
<tr>
<td>D</td>
<td>0...20 mA</td>
<td>&lt;1.0 µA</td>
<td>100,000</td>
</tr>
</tbody>
</table>

### BTA-LIN

- 0...10 Volt or 4...20 mA
- Analog Input
- 5 digit, LED display
- Optional 4 setpoint
- 5 A relay output

### Example Calculation

<table>
<thead>
<tr>
<th>Positional Accuracy</th>
<th>Full Scale Length</th>
<th>Total Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>610 mm</td>
<td>100,000</td>
<td>0.000244 in</td>
</tr>
</tbody>
</table>
Balluff Linear Displacement Transducers offer non-contact, wearfree, and accurate linear positioning for industrial environments wherever linear motion must be controlled. The sensing element is enclosed in either an anodized stainless steel rod or an extruded aluminum housing. The absolute position is detected by a non-contact magnet that is attached to the moving member of the machine. The output is an analog signal, with no need to re-home after a power interruption.

Shown below are the housing configurations available for the BTL-2 transducers. The BTL-2-...-Z "Rod Style" version is designed for installations in hydraulic and pneumatic cylinder applications. The BTL-2-...-F "Captive Magnet" and the BTL-2-...-P "Floating Magnet" versions are designed to the same formats as linear potentiometers for use in general positioning control.

BTL-2-...-F: "Captive Magnet" version transducers are designed to be used when the mechanics of the system require a sliding motion for the point of contact for positioning. The magnet slides along the top of the transducer housing on special guides and connects to the system via a swivel ball joint.

BTL-2-...-P: "Floating Magnet" version transducers are designed to be used where the positioning mechanism can glide along a path above the transducer at a close range.

BTL-2-...-Z: "Rod Style" version transducers are designed to be used in hydraulic cylinder position control. The magnet (ring style) is attached directly to the piston face sliding over the transducer rod.
BTL2-A__ Signal Description

Dual analog voltage output signals are available with this version as: 0...10, and 10...0 V DC. Resolution is 0.001 % of Full Scale (10 V) which gives the smallest measurable signal change as 0.1 mV DC. The output signals are valid across the length denoted by "xxxx". Maximum current loading is 10 mA.

BTL2-B__

Dual analog voltage output signals are available with this version as: -5...+5, and +5...-5 V DC. Resolution is 0.001 % of Full Scale (10 V) which gives the smallest measurable signal change as 0.1 mV DC. The output signals are valid across the length denoted by "xxxx". Maximum current loading is 10 mA.

BTL2-C__

Dual analog voltage output signals are available with this version as: -10...+10, and +10...-10 V DC. Resolution is 0.001 % of Full Scale (10 V) which gives the smallest measurable signal change as 0.1 mV DC. The output signals are valid across the length denoted by "xxxx". Maximum current loading is 10 mA.

BTL2-D__

Analog current output signals are available with this version as either: 0...20, or 20...0 mA DC. Resolution is 0.001 % of Full Scale (20 mA) which gives the smallest measurable signal change as <1.0 μA DC. The output signals are valid across the length denoted by "xxxx". Maximum current loading is 500 ohms.

BTL2-E__

Analog current output signals are available with this version as either: 4...20, or 20...4 mA DC. Resolution is 0.001 % of Full Scale (20 mA) which gives the smallest measurable signal change as <1.0 μA DC. The output signals are valid across the length denoted by "xxxx". Maximum current loading is 500 ohms.
Technical Specifications

- Power Voltage (±11) ...±24 V DC ±10%
- Power Voltage (±21) ...±15 V DC ±2%

- Current Draw:
  - BTL-2-11 ... 130 mA (±24 V DC)
  - BTL-2-21 ... 100/60 mA (±15 V DC)

- Linearity:
  - (Di ≤500 mm) ... ±150 µm (±0.01 in.)
  - (Di >500 mm) ... ±0.00% of Full Scale

- Resolution (all types):
  - (0...10 V types) ... ±0.1 mV DC
  - (±5...±6 V types) ... ±0.1 mV DC
  - (0...20 mA types) ... ±0.1 µA DC
  - (4...20 mA types) ... ±0.1 µA DC

- Hysteresis: 200 mV (0.00008 in.)

- Accuracy: Resolution + Hysteresis

- Sampling Rate: 1 kHz (per update)

- Operating Temp: -25...+60°C

- Storage Temp: -25...+125°C

Interface Information

The BTL-2 analog output series transducers interface with either analog voltage or current input control systems depending on model type. To retain the high resolution analog signals possible with the BTL-2 transducers, care should be taken when specifying a DC power supply and routing electrical cables. The BTL-2 current output transducers (-C and -E types) offer higher noise immunity over the voltage output types. The analog current output signals can be converted to a DC voltage signal by placing a load resistance of 500 ohms across the signal output at the control system's input terminals. This 500 ohm load would convert the 0...20 mA signal into 0...10 VDC at the control input end.

Shielding and Grounding

Balluff's standard cable is 22/6/G multiconductor type with overall braided shield. To reduce external noise, the cable shield must be properly used. Connect the cable shield to the control system GND. The cable shield is not connected at the BTL2 transducer end. Use a 2.2 µF non-polarized type capacitor to suppress any noise that appears on signal lines. Always observe proper grounding techniques such as single point earthing and isolating high voltage (i.e. 120/240 VAC) from voltage (24 VDC) cables. Diagram at right.
### S50 Connector Pinouts for Analog Output Transducers - "Profile" Housing Style

**For: BTL-2-A/B/G11** (+24V supply), and BTL-2-A/B/G21 (+15V supply)

<table>
<thead>
<tr>
<th>Cable Wire Color</th>
<th>S50 Pin No.</th>
<th>Function</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>yellow</td>
<td>1</td>
<td>Not used</td>
<td>N/A</td>
</tr>
<tr>
<td>grey</td>
<td>2</td>
<td>Signal GND</td>
<td>N/A</td>
</tr>
<tr>
<td>pink</td>
<td>3</td>
<td>Vout falling</td>
<td>N/A</td>
</tr>
<tr>
<td>blue</td>
<td>4</td>
<td>Supply GND</td>
<td>N/A</td>
</tr>
<tr>
<td>brown</td>
<td>5</td>
<td>(+) 24V or 15V</td>
<td>N/A</td>
</tr>
<tr>
<td>green</td>
<td>6</td>
<td>Vout rising</td>
<td>N/A</td>
</tr>
<tr>
<td>white</td>
<td>center</td>
<td>(-) 15V</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**For: BTL-2-C/E10** (+24V supply), and BTL-2-C/E20 (+15V supply)

<table>
<thead>
<tr>
<th>Cable Wire Color</th>
<th>S50 Pin No.</th>
<th>Function</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>yellow</td>
<td>1</td>
<td>Voltage</td>
<td>Current</td>
</tr>
<tr>
<td>grey</td>
<td>2</td>
<td>N/A</td>
<td>0-20 or 4-20mA*</td>
</tr>
<tr>
<td>pink</td>
<td>3</td>
<td>N/A</td>
<td>Signal GND</td>
</tr>
<tr>
<td>blue</td>
<td>4</td>
<td>N/A</td>
<td>not used</td>
</tr>
<tr>
<td>brown</td>
<td>5</td>
<td>N/A</td>
<td>Supply GND</td>
</tr>
<tr>
<td>green</td>
<td>6</td>
<td>N/A</td>
<td>not used</td>
</tr>
<tr>
<td>white</td>
<td>center</td>
<td>N/A</td>
<td>(-) 15V</td>
</tr>
</tbody>
</table>

*rising only

**For: BTL-2-C/E17** (+24V supply), and BTL-2-C/E27 (+15V supply)

<table>
<thead>
<tr>
<th>Cable Wire Color</th>
<th>S50 Pin No.</th>
<th>Function</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>yellow</td>
<td>1</td>
<td>Voltage</td>
<td>Current</td>
</tr>
<tr>
<td>grey</td>
<td>2</td>
<td>N/A</td>
<td>20-0 or 20-4 mA*</td>
</tr>
<tr>
<td>pink</td>
<td>3</td>
<td>N/A</td>
<td>Signal GND</td>
</tr>
<tr>
<td>blue</td>
<td>4</td>
<td>N/A</td>
<td>not used</td>
</tr>
<tr>
<td>brown</td>
<td>5</td>
<td>N/A</td>
<td>Supply GND</td>
</tr>
<tr>
<td>green</td>
<td>6</td>
<td>N/A</td>
<td>not used</td>
</tr>
<tr>
<td>white</td>
<td>center</td>
<td>N/A</td>
<td>(-) 15V</td>
</tr>
</tbody>
</table>

*falling only
Linear Displacement Transducer
Series BTL-2
Analog Output Transducers
Mechanical Specifications

Profile Styles Standard Lengths (All Outputs)

<table>
<thead>
<tr>
<th>Electrical Stroke (mm)</th>
<th>Electrical Stroke (in.)</th>
<th>Physical (mm)</th>
<th>Physical (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0102</td>
<td>0.4</td>
<td>261.0</td>
<td>10.2</td>
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<td>0.6</td>
<td>312.4</td>
<td>12.3</td>
</tr>
<tr>
<td>0200</td>
<td>0.8</td>
<td>388.0</td>
<td>15.3</td>
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<tr>
<td>0254</td>
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<td>0305</td>
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<td>17.5</td>
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<td>541.0</td>
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<td>0407</td>
<td>1.6</td>
<td>544.4</td>
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<td>0457</td>
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<td>0505</td>
<td>2.0</td>
<td>668.0</td>
<td>26.2</td>
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<tr>
<td>0510</td>
<td>2.4</td>
<td>769.6</td>
<td>30.3</td>
</tr>
<tr>
<td>0572</td>
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<td>36.3</td>
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<td>0914</td>
<td>3.6</td>
<td>1074.4</td>
<td>42.3</td>
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</table>

(Captive and Floating Magnet Styles)
Ordering Code for Analog Output Transducers

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<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<th>20</th>
<th>21</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>T</td>
<td>L</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>A</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>5</td>
<td>-</td>
<td>Z</td>
<td>-</td>
<td>S</td>
<td>5</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- BTL - Transducer - Linear - Generation 2

Output Signal:
- A = 0...10 V
- B = -5...+5 V
- C = 0...20 mA
- E = 4...20 mA
- G = -10...+10 V

Supply Voltage:
- 1 = 24 V ±10%
- 2 = ±15 V ±2%

Output Signal:
- If A, B, or G in position 7:
  - 1 = Vmin or Vmax at connector end, i.e. user selectable rising or falling*
  - 0 = Vmin at connector end only, i.e. rising only**
  - 7 = Vmax at connector end only, i.e. falling only**

- If C or E in position 7:
  - 0 = Vmin at connector end (rising towards opposite end)
  - 7 = Vmax at connector end (falling towards opposite end)

Nominal stroke in mm
- 0305 = 305 mm active electrical stroke

Housing geometry:
- B = Rod style with M18x1.5 thread and reference point 30 mm from flange (European standard)
- F = Profile extrusion with captive magnet
- P = Profile extrusion for floating magnet
- Z = Rod style with 3/4"-16 UNF thread and reference point 2 in. from flange (USA standard)

Connection type:
- S10 = connector with pin contacts, 7-pole, form 50 (not available for analog rod-style)
- S12 = connector with pin contacts, 8-pole, form 32 (not available on "F" or "P" style)
- KA05 = integral axial cable (with 5 m cable) only if "B" or "Z" in position 18, not available in "F" or "P" style

Notes:
* Use "1" for new application only, or consult factory if used as replacement
** Use "0" or "7" for exact pin compatibility with older BTL models. Examples:
- Exact replacement for BTL-A16-xxxx-Z-S32 is BTL-2-A10-xxxx-Z-S32
- Exact replacement for BTL-A16-xxxx-Z-S32 is BTL-2-A17-xxxx-Z-S32
- Exact replacement for BTL-E16-xxxx-Z-S32 is BTL-2-E10-xxxx-Z-S32
- Exact replacement for BTL-E28-xxxx-Z-KA02 is BTL-2-E27-xxxx-Z-KA02

Magnet rings or blocks must be ordered separately, except "F" style profile, where Balluff p/n BTL-Z-2-2413-3 slide magnet assembly is included at no charge and does not have to be ordered separately.

Consult factory for special part numbers denoting outputs such as 0...5V, special null points, etc.
Linear Displacement
Transducer
Series BTL-2
Analog Output Transducers
Ordering Code Worksheet

Worksheet - Create your BTL-2 Part Number (for digital pulse output, see pages G29 and G29).

Output Signal
Fill in A, B, C, E or G
This specifies the output range only, not whether increasing or decreasing with direction of motion. Position 9 will be used to define this specification.

Supply Voltage
Fill in 1 or 2
This specifies the supply voltage required.

Output Orientation
Fill in 1, 0 or 7.
A "1" is only allowed for voltage output (A, B or G output). The "1" means that two pins (leads) have a position output signal:
one carries the voltage increasing in value as the magnet moves
away from the connector/cable end of the transducer, and the
other carries the voltage decreasing in value as the magnet moves
away from the connector/cable end. The user may use either
current output, but not both at the same time.
A "0" or "7" must be used to designate direction for current outputs
(C or E), and may be used with voltage outputs if the BTL2
is replacing an older model (see notes previous page). If "0" or "7"
is specified with voltage output, only one output signal is
available (increasing or decreasing).

Nominal Stroke in mm
Fill in stroke length in mm, using leading zero if necessary.
See pages G16 and G17 for list of standard lengths available for both rod and profile style housings. The nominal stroke represents the electrical stroke, that is the travel distance over which the full output range is measured. For example, 9905 means that 0...10 V, or 4...20
mA etc. is output over a distance of 995 mm (12 inches). On either side of this nominal stroke area are zones where the magnet is normally not allowed to travel.

Housing Geometry
Fill in B, F, P or Z.
This specifies the housing style or mounting thread size. "B" and "Z" mean rod-style housing, M16 or 3/4"-16 UNF respectively. Standard (stocked) thread is 3/4-inch. "F" and "P" refer to "profile"-style housing, "F" means captive magnet version and "P" means floating magnet version.

Connection Type
Fill in S50, S32 or KAxr.
This specifies the connection method, either with quick-disconnect axial connector, or Integral cable. For analog output, the rod-style is available with S32 connector or integral cable only (S50 not available). Digital pulse output rod-style is available with S50 or S32 connector or integral cable. Profile housing (digital pulse or analog) is available with S50 connector only (integral cable not available).
No-Mount
Tie-Rods Extended Head End
Parker Series EH
Electrohydraulic Actuator

No Mount
Parker Style T — All Feedback Types

Tie-Rods Extended Head End
Parker Style TB — All Feedback Types

Rod End Dimensions — See Table 2

Special Thread Style 3
Special thread, extension, rod eye, blank, etc., are also available.
To order, specify "Style 3" and give desired dimensions for CC or KK, A and LA.
If otherwise special, furnish dimensioned sketch. For female threads, see page 152.

For additional information — call your local Parker Fluidpower Motion & Control Distributor.
Quotation # 1213

TO MARTIN MARITTA ENERGY SYSTEMS
ORNL
ROBOTICS & PROCESS CONTROL
OAK RIDGE, TN 37830
ATTN: BRETT KABAUS

WE ARE PLEASED TO QUOTE THE FOLLOWING FOR YOUR CONSIDERATION:

PARKER HYDRAULIC ROTARY ACTUATOR MODEL #NTR30-360-AB11WX
X = LT FEED BACK PACKAGE CONSISTING OF TEMPOSONICS II
LT WITH ATM -10VDC TO +10VDC POSITION ONLY. ALSO INCLUDES
MATING CONNECTOR WITH 15 FT. CABLE FOR TRANSDUCER

$3637.00 EA.

SHIPPING PROMISE
4 TO 5 WEEKS

1. This and other information from Hoyt N. Payne Co. Provide product or system options for further investigation by users having technical expertise before you select or use any product or system. It is important that you analyze all aspects of your application and review the information concerning the product in the current product catalog. The user, through its own analysis and testing, is solely responsible for making the final selection of the system and components and assuring that all performance safety and warning requirements of the application are met.

2. This quotation is made subject to the terms and conditions listed herein and the standard terms and conditions of the suppliers of the materials quoted. Copies available on request.

3. Seller's liability with respect to any item not of seller's manufacture shall be limited to that of the Vendor thereof.

4. Unless otherwise specified, prices quote herein are subject to revision to the prices which are in effect at the time shipment is made.

5. If an order is received for the items quoted herein, it will not be subject to cancellation without indemnifying both the suppliers of the materials quoted and the Hoyt N. Payne Co. against loss.

6. Unless specifically stated otherwise, in no event shall seller be liable here under or otherwise for loss of profit, special, incidental or consequential damages.
Brett, here is a drawing on your rotary actuator. Thought you may want it before it shows up.

Jack
end mass v/s freq.
<table>
<thead>
<tr>
<th>density [lbm/in³]</th>
<th>0.28</th>
<th>extend lgth [in]</th>
<th>72</th>
</tr>
</thead>
<tbody>
<tr>
<td>length [in]</td>
<td>96</td>
<td>E-beam [lb/in²]</td>
<td>3.00E+07</td>
</tr>
<tr>
<td>diameter [in]</td>
<td>1</td>
<td>Icsa [in⁴]</td>
<td>0.04908739</td>
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<tr>
<td>mass [lbm]</td>
<td>21.1115026</td>
<td>end mass [lbm]</td>
<td>120</td>
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<tr>
<td>Ixx [lbm·in²]</td>
<td>2.63893783</td>
<td>K-beam [lb/in]</td>
<td>11.8362715</td>
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<tr>
<td>tot move lgth</td>
<td>48</td>
<td>w [rad/sec]</td>
<td>6.17355605</td>
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<tr>
<td>up time [s]</td>
<td>0.25</td>
<td>w [Hz]</td>
<td>0.98255196</td>
</tr>
<tr>
<td>const time [s]</td>
<td>0.5</td>
<td>end deflect [in]</td>
<td>10.1383278</td>
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<tr>
<td>dwn time [s]</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tot run time [s]</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vmax [in/s]</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rod accel [in/s]</td>
<td>256</td>
<td>extend lgth [in]</td>
<td>24</td>
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<td>force reqd [lb]</td>
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<td>force req [lbf]</td>
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</tr>
<tr>
<td>K-beam [lb/in]</td>
<td>319.579331</td>
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<td></td>
</tr>
<tr>
<td>w [rad/sec]</td>
<td>32.0787382</td>
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<tr>
<td>w [Hz]</td>
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<td>end deflect [in]</td>
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<td>extend lgth [in]</td>
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<td>length [in]</td>
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<td>E-beam [lb/in²]</td>
<td>3.00E+07</td>
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<tr>
<td>diameter [in]</td>
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<td>Icsa [in⁴]</td>
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<tr>
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<td>end deflect [in]</td>
<td>0.23636017</td>
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<td>dwn time [s]</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>tot run time [s]</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vmax [in/s]</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rod accel [in/s]</td>
<td>256</td>
<td>extend lgth [in]</td>
<td>24</td>
</tr>
<tr>
<td>force reqd [lb]</td>
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<td>Icsa [in⁴]</td>
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</tr>
<tr>
<td>end mass [lbm]</td>
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<td></td>
</tr>
<tr>
<td>K-beam [lb/in]</td>
<td>1142.32446</td>
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<tr>
<td>w [rad/sec]</td>
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</tr>
<tr>
<td>w [Hz]</td>
<td>33.4374714</td>
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<td></td>
</tr>
<tr>
<td>end deflect [in]</td>
<td>0.00875408</td>
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</tr>
</tbody>
</table>
HOUGHTO - SAFE® 620

fire-resistant water-glycol hydraulic fluid gives long pump life

There is a hazard wherever heat, molten metal or flame are near hydraulic equipment. If a line or fitting ruptures, it can send a combustible spray of oil into the heat source. Severe injury and property damage may result.

To prevent this danger, fire-resistant fluids were developed and widely applied early in the 1950's. Houghton, a pioneer in fortifying petroleum hydraulic oils, was among the first to perfect fire-resistant fluids for hydraulic use.

Houghto-Safe 620 was developed as a maximum safety medium for use, under pressure, near open flame or high temperature areas.

Houghto-Safe 620 is a red, extremely "oily" hydraulic fluid that protects against corrosion and has additives to give long fluid life and excellent pump wear characteristics.

Houghto-Safe 620 gives maximum safety. In plant use it has prevented hundreds of fires and saved lives of workers. 620 is approved by Factory Mutual Engineering Laboratories as a less hazardous hydraulic fluid.

Houghto-Safe 620 provides high hydraulic efficiency through its exceptionally high viscosity index and is stable under high shearing stresses. Houghto-Safes are also available in other viscosities.

In accordance with accepted practice, it is recommended that bulk fluid temperatures be maintained below 120°F.

Applications

Houghto-Safe 620 is used in virtually every type of hydraulic equipment to help prevent the danger of fire:

Forging Presses and Extrusion Presses
Glass Feeder and Forming Machines
Ingot Manipulators
Fork Lift Trucks
Clamping Fixtures on Automatic Welders
Scarfing Machines
Flying Shears
Cranes, Hoists and Elevators
Rod and Strip Coilers
Rod Mill, Tube Mill, and Hot Strip Mill
Crushers
Planetary Mills
Screw Down Controls
Ladle Stoppers
Auto Pours Units
Trimmers
Furnace Door Controls
Coupling Tighteners
Roll Jinks and Roll Balance Controls
Lift and Transfer Tables
Plate Milling Machines
Grid Machines
Straddle Trucks

Typical Physical Properties

Viscosity, SUS at 0°F. 3000
70°F. 386
100°F. 199
130°F. 117
150°F. 89

Viscosity Index
Old Method (ASTM D567) 154
New Method (ASTM D2270) 201

Pour Point, °F. -65

pH 8 to 10

Specific Gravity at 60°F. 8.36

Pour Point (ASTM) Not applicable

Flash Point (ASTM) 0.71

Color Red

Specific Heat at 60°F. 0.26

Viscosity, SUS at 120°F. 0-00

Lubricity and Pump Life

The high lubricity of Houghto-Safe 620 is shown in these typical pump tests in widely used vane type and intravane type pumps.

Test conditions

<table>
<thead>
<tr>
<th>Test period, hours</th>
<th>Vane type pump</th>
<th>Intravane type pump</th>
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</thead>
<tbody>
<tr>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Pressure, psi</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Sump temp., °F.</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>Pump speed, rpm</td>
<td>1200</td>
<td>1200</td>
</tr>
</tbody>
</table>

Test results after 500 hours

<table>
<thead>
<tr>
<th>Wear on ring, gms</th>
<th>Wear on intravane type pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.09</td>
</tr>
<tr>
<td>Wear on vane gms</td>
<td>0.045</td>
</tr>
<tr>
<td>Wear on intravane set, gms</td>
<td>0.099</td>
</tr>
<tr>
<td>Fluid</td>
<td>No significant change</td>
</tr>
</tbody>
</table>

This is very low wear! Many years of service can be expected under typical operating conditions.
**Bertelkamp Automation, Inc.**

**Industrial Automation Specialists**

P.O. Box 11643 / KNOXVILLE, TN 37939-1643
615-588-7891 / 800-251-9134
FAX: 615-588-9445

From: Mike Little To: Reid Kress - ORNL

**Quotation**

**Date:** 22-Aug-95  
**Time:** 09:35 AM

**Quotation No.:** ORNL0822

**Revision:**

**Your inquiry:**

**Reference:** Update of ORNL0816

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
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<th>Description</th>
<th>Unit price</th>
<th>Ext price</th>
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</thead>
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<tr>
<td>1</td>
<td>144</td>
<td>3030</td>
<td>3&quot; X 3&quot; Heavy Wall T-Slotted Extrusion (4) at 36&quot;</td>
<td>$1.39</td>
<td>$200.16</td>
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<tr>
<td>2</td>
<td>228</td>
<td>1530</td>
<td>1.5&quot; X 3&quot; Heavy Wall T-Slotted Extrusion (8) at 18&quot; (4) at 21&quot;</td>
<td>$0.88</td>
<td>$200.64</td>
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<tr>
<td>3</td>
<td>4</td>
<td>7030</td>
<td>Cut To Length 3030</td>
<td>$2.45</td>
<td>$9.80</td>
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<tr>
<td>4</td>
<td>12</td>
<td>7020</td>
<td>Cut To Length 1530 and 1530-Lite</td>
<td>$2.30</td>
<td>$27.60</td>
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<td>5</td>
<td>4</td>
<td>2410</td>
<td>3030 Floor Mount Base Plate</td>
<td>$35.60</td>
<td>$142.40</td>
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<tr>
<td>6</td>
<td>8</td>
<td>4328</td>
<td>12 Hole 90 Degree Joining Plate</td>
<td>$12.25</td>
<td>$98.00</td>
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<td>7</td>
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<td>4525</td>
<td>12 Hole Tee Joining Plate</td>
<td>$12.25</td>
<td>$98.00</td>
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<td>8</td>
<td>2</td>
<td>4355</td>
<td>8 Hole Tee Joining Plate</td>
<td>$9.05</td>
<td>$18.10</td>
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<td>6</td>
<td>4366</td>
<td>6 Hole Joining Plate</td>
<td>$5.55</td>
<td>$33.30</td>
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<tr>
<td>10</td>
<td>4</td>
<td>4301</td>
<td>4 Hole Inside Corner Bracket</td>
<td>$4.05</td>
<td>$16.20</td>
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<tr>
<td>11</td>
<td>146</td>
<td>3555</td>
<td>5/16-18 X 5/8&quot; Flanged BHSCS, Double Economy T-Nut</td>
<td>$1.39</td>
<td>$202.94</td>
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<tr>
<td>12</td>
<td>24</td>
<td>4375</td>
<td>6 Hole Inside Corner Bracket</td>
<td>$6.10</td>
<td>$146.40</td>
</tr>
<tr>
<td>13</td>
<td>98</td>
<td>3320</td>
<td>5/16-18 X 5/8&quot; Flanged BHSCS &amp; Economy T.Nut</td>
<td>$0.57</td>
<td>$54.72</td>
</tr>
<tr>
<td>14</td>
<td>30</td>
<td>1010</td>
<td>1&quot; X 1&quot; T-Slotted Extrusion (1) at 30&quot;</td>
<td>$0.21</td>
<td>$6.30</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>7005</td>
<td>Cut To Length 1010</td>
<td>$1.85</td>
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<td>16</td>
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<td>2380</td>
<td>1010 Floor Mount Base Plate</td>
<td>$21.10</td>
<td>$42.20</td>
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<tr>
<td>17</td>
<td>4</td>
<td>3356</td>
<td>1/4-20 X 1/2&quot; Flanged BHSCS,Double Economy T-Nut</td>
<td>$0.90</td>
<td>$3.60</td>
</tr>
</tbody>
</table>

**Quotations are firm for a period of 30 days unless otherwise specified.**

F.O.B. Shipping point: BY:

Terms: 1% 10, net 30

Quotation Total: $1,302.21

**BY:**

Mike Little
#include "filter.hh"

extern "C"
{
    void filmain(void);
}

void filmain(void)
{
    // Create filter parameter vectors
    RowVector b(5);
    RowVector a(4);
    b[0]=0.0048;
    b[1]=0.0193;
    b[2]=0.0289;
    b[3]=0.0193;
    b[4]=0.0048;
    a[0]=2.3695;
    a[1]=-2.314;
    a[2]=1.0547;
    a[3]=-0.1874;
    // Build Filter object Butter
    Filter Butter(b,a);
    // Run the filter on some data
    double sign=1;
    for(int j=0;j<10;j++)
    {
        sign=-1*sign;
        for(int i=0;i<50;i++)
        {
            double u=10*sign;
            double y=Butter.Update(u);
            printf("Input = %lf and Output = %lf",u,y);
        }
    }
}
```cpp
#include "filter.hh"

Filter::Filter() : theta(1), phi(1) {
    FilterOrder = theta.GetVecSize() + phi.GetVecSize();
    NumOrder = theta.GetVecSize();
    DenOrder = phi.GetVecSize();
}

Filter::Filter(Filter &tmpFilter)
    : theta(tmpFilter.theta), phi(tmpFilter.GetFilterOrder()) {
    FilterOrder = tmpFilter.GetFilterOrder();
    NumOrder = tmpFilter.GetNumOrder();
    DenOrder = tmpFilter.GetDenOrder();
}

Filter::Filter(RowVector numtmp, RowVector dentmp)
    : theta(numtmp, dentmp), phi(numtmp.GetVecSize() + dentmp.GetVecSize()) {
    FilterOrder = numtmp.GetVecSize() + dentmp.GetVecSize();
    NumOrder = numtmp.GetVecSize();
    DenOrder = dentmp.GetVecSize();
}

Filter::Filter(int numorder, int denorder)
    : theta(numorder + denorder), phi(numorder + denorder) {
    FilterOrder = numorder + denorder;
    NumOrder = numorder;
    DenOrder = denorder;
}

Filter & Filter::operator = (Filter & filter1) {
    if ((filter1.NumOrder == NumOrder) & (filter1.DenOrder == DenOrder)) {
        theta = filter1.theta;
        phi = filter1.phi;
    } else {
        printf("\nFilters are incompatible in Filter class!\n");
        exit(0);
    }
    return *this;
}

void Filter::print(void) {
    printf("Order of Num is %d", NumOrder);
    printf("and Order of Den is %d", DenOrder + 1);
    printf("Parm Vector = ");
    theta.print();
}

// Actual filtering process; u is input stream
double Filter::Update(double u) {
    double y;
    for (int i = NumOrder - 1; i > 0; i--) {
        phi[i] = phi[i - 1];
        phi[0] = u;
        y = theta * phi;
        for (i = (DenOrder + NumOrder - 1), i > NumOrder, i--)
            phi[i] = phi[i - 1];
    }
    return y;
}
```
// Filter Class
//
// General Form Y(z) = \frac{B_0 + B_1 z^{-1} + \ldots + B_n z^{-n}}{1 - A_1 z^{-1} - \ldots - A_n z^{-n}}
//
// Constructor is passed 2 vectors, num and den.
// num gives the vector parameters of the numerator coef. of the filter
// den gives the vector parameters of the denominator coef. Note the form
// above. The filter
//
// \frac{2 + 3z^{-1}}{1 + 0.25z^{-1} + 3z^{-2}}
//
// would have num=[2 3] and den=[-0.25 -3];
//
// Parameter Vector, theta, is a row vector, [a b ...]
// and State Vector, phi, is a column vector, [x y z ...]'
// output of filter is y[k]=theta*phi
//
#if !defined(FILTER_HH)
#define FILTER_HH 1
#endif

#include "matrix.hh"

class Filter
{
public:
  Filter();
  ~Filter(); { Delete(); };
  Filter(RowVector numparms, RowVector denparms);
  Filter(int numord, int denord);
  Filter(Filter &tmpFilter);
  Filter & operator = (Filter &Filterl);
  void print(void);
  double Update(double u);
  int GetFilterOrder(void){ return FilterOrder; }
  int GetNumOrder(void){ return NumOrder; }
  int GetDenOrder(void){ return DenOrder; }

protected:
  int NumOrder;
  int DenOrder;
  int FilterOrder;
  RowVector theta;
  ColVector phi;
  void Delete (void)
  {
    NumOrder=0;
    DenOrder=0;
  }
};
#endif
cd "/uO/love/control"
ld < filtest.V
Listing for Lonnie Love

FILE: Bode.C
AUTHOR: Lonnie J. Love
VERSION: 1.4
MODIFIED: 12 Jun 1996 09:00:18
DESCRIPTION:

HISTORY:

# Date       By         Comment
#--------------------------------------------------------------------------
1.5 06/03/96  LJL      Changed to FlexController Class
1.4 08/09/95  PMR     Broke program into controller and new Robot class
1.3 08/09/95  PMR     Added load cell bias voltage monitor
1.2 07/09/95  PMR     Passed analog input tests
1.1 06/15/95  PMR     Full humanAmp capabilities demonstrated in
                       both NORMAL and BODE modes
1.0 06/12/95  PMR     Initial file creation.

// Embedded sccs id string:
static char sccs_Bode_C[] = "@CilBode.C 1.4"

FUNCTION NAME: startBode_vf ( )
DESCRIPTION: Kick off the task to create and maintain the Bode controller object

void startBode_vf(void)
{
    if( startTaskId_i || terminationSem_a )
        logMsg( "Controller already running\n", 0,0,0,0,0,0 );
    else
        startTaskId_i = taskSpavm( "CHAStart",
            9, 0, //VX_FP_TASK,
            5000, (FUNCPTR) BodeTask_if,
            0, 0, 0, 0, 0, 0, 0, 0, 0, 0 );
}

FUNCTION NAME: BodeTask_if ( )
DESCRIPTION: Task which creates and maintains the Bode controller

int BodeTask_if( void )
{
    time_t bintime;
    logMsg( "BodeTask_if: Starting Bode controller\n", 0,0,0,0,0,0 );
    // Create the semaphore used to terminate this task
    terminationSem_a = semBCreate(0,SEM_EMPTY);
    // Create the instance of the Bode controller
    BodeController controller_a;
    printf("Built Bode Controller\n");
    // Wait for the termination sem to be given by the stopBode_vf func.
    semTake( terminationSem_a, WAIT_FOREVER );
    // Delete the termination sem
    semDelete( terminationSem_a );
    terminationSem_a = (SEM_ID) NULL;
    startTaskId_i = 0;
    // Close the file
    fprintf( "BodeTask_if: Stopping Bode controller\n", 0,0,0,0,0,0 );
    return(OK) ;
}

FUNCTION NAME: stopBode_vf ( )
DESCRIPTION: Kill off the controller

void stopBode_vf(void)
{
    if( startTaskId_i || terminationSem_a )
        semGive( terminationSem_a );
}

METHOD NAME: BodeController ( )
DESCRIPTION: Constructor method

```
BodeController::BodeController(void )
```
decay = 1.0 - exp(-((elapsedRunTime_d - 0.5 * timeHome_Cd) / 7.5));
error = (initialJointPosition +
  decay * (desiredPosition - initialJointPosition))
  - jointPosition;

// Now start doing Bode stuff

if (FREQ_COMPLETE == TRUE)
{
  FREQ_COMPLETE = FALSE;
  if (FIRST == TRUE)
  {
    FIRST = FALSE;
    FreqIndex = 0;
  }
  else
  {
    // Compute the magnitude and phase before resetting constants
    Magnitude = (2 / NumDataPoints) * sqrt(B0 * B0 + CO * CO) / AO;
    Phase = 180.0 * atan2(C0, B0) / 3.14159265;
    // Write results to a file
    fprintf(fname, "%6.41f %3.11f %6.41f %6.41f %7.41f\n",
      AO, Frequency[FreqIndex], Magnitude, Phase, elapsedRunTime_d);
    printf("Freq=%3.11f Mag=%6.41f Phase=%6.41f Time=%7.41f\n",
      Frequency[FreqIndex], Magnitude, Phase, elapsedRunTime_d);
    // Increment to the next frequency and cycle back to first freq. if
    // the index exceeds the number of frequencies investigated
    FreqIndex++;
    if (FreqIndex >= NumOfFreq)
      FreqIndex = 0;
  }
  // Compute the number of data points necessary to create ten cycles
  // at the selected frequency and convert to rad/sec.
  NumDataPoints = int(10 * (sampleFreq_d / Frequency[FreqIndex]));
  omega = 2 * 3.14159265 * Frequency[FreqIndex] / sampleFreq_d;
  // Reset all necessary counters
  DataPoint = 0;
  tick_ul = 0;
  elapsedRunTime_d = 0;
  AO = 0;
  CO = 0;
}

else
{
  // Compute the command to the desired joint
  double error[2];
  error[0] = jointPosition[MotorJoint] * cos(omega * DFTCount);
  error[1] = jointPosition[MotorJoint] * sin(omega * DFTCount);
  if (DataPoint >= NumDataPoints)
    FREQ_COMPLETE = TRUE;
  
  if ((compensatorR_ap->Next(error[ROTARY], &controlOut[ROTARY]) != 1) ||
      (compensatorP_ap->Next(-1.0 * error[PRISMATIC], &controlOut[PRISMATIC]) != 1))
    jointCommand = Zero;
  else
    jointCommand = controlOut;
  // Write the analog outputs
  flexArm.SetCommand(jointCommand);
}
```c
/*
 * Oak Ridge National Laboratory
 * Robotics and Process Systems Division
 * U. S. Government internal use only
 *
 * FILE: Bode.H
 * AUTHOR: Lonnie J Love
 * VERSION: 1.0
 * MODIFIED: 19 Jan 1996 09:01:34
 * DESCRIPTION:
 *
 * HISTORY:
 * # Date     By                Comment
 * 1.3 08/09/95 PMR  -Added load cell bias voltage monitor
 *                  -Passed analog input tests
 * 1.2 07/05/95 PMR  -Full humanAmp capabilities demonstrated in
 *                  both NORMAL and BODE modes
 *                  -HUMAN_MODELING_TEST not finished yet
 * 1.1 06/15/95 PMR  -Checked into SCCS.
 * 1.0 06/12/95 PMR  -Initial file creation.
 */

// Embedded access id string:
static char sccs_Bode_H[] = "@(#)Bode.H 1.1";

#ifndef BODE_H
#define BODE_H

#define MAX_NUMBER_OF_POINTS 10; // maximum number of points for a path

int startTaskId_i = 0;
SEM_ID terminationSem_a = (SEM_ID) NULL;

// C++ includes
#include "IP-padc.H"
#include "IP-dac.H"
#include "IP-dig24.H"
#include "processClass.H"
#include "compensator.H"
#include "Robot.H"
#include "matrix.H"

class BodeController : processClass
{
  public:
    BodeController( void );
    ~BodeController( void )
    {}
    if( compensatorP_ap ) delete compensatorP_ap;
    if( compensatorR_ap ) delete compensatorR_ap;
    if( startTaskId_i ) startTaskId_i = 0;
    if( terminationSem_a )
      semDelete( terminationSem_a );
    terminationSem_a = (SEM_ID) NULL;
    printf("\nBodeController Destroyed..\n");
  }

private:
#endif
```
FUNCTION NAME: startBode_vf
DESCRIPTION: Kick off the task to create and maintain the Bode controller object

void startBode_vf(void)
{
  if( startTaskId_i || terminationSem_a )
    logMsgf( "Controller already running\n", 0,0,0,0,0,0 );
  else
    startTaskId_i = taskSpawn( "tHAStart", 9, 0, VX_FP_TASK, 5000, (FUNCPTTR) BodeTask_if,
                             0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0);
}

FUNCTION NAME: BodeTask_if
DESCRIPTION: Task which creates and maintains the Bode controller

int BodeTask_if( void )
{
  time_t bintime;
  time(&bintime);
  logMsgf( "BodeTask_if: Starting Bode controller\n", 0,0,0,0,0,0 );
  // Create the semaphore used to terminate this task
  terminationSem_a = semBCreate(0,SEM_EMPTY);
  // Create the instance of the Bode controller
  BodeController controller_a;
  printf("Built Bode Controller\n");
  // Wait for the termination sem to be given by the stopBode_vf func.
  semTake( terminationSem_a, WAIT_FOREVER );
  semDelete( terminationSem_a = (SEM_ID) NULL;
  startTaskId_i = 0;
  fclose(fname);
  printf( "BodeTask_if: Stopping Bode controller\n", 0,0,0,0,0,0 )
  return(OK);
}

FUNCTION NAME: stopBode_vf
DESCRIPTION: Kill off the controller

void stopBode_vf( void )
{
  if( startTaskId_i &fc terminationSem_a )
    semGive( terminationSem_a );
}

METHOD NAME: BodeController()
DESCRIPTION: Constructor method

BodeController::BodeController( void ) :
  processClass( "TCAMCtrl", 100, 0, 5000, MANUAL_startMeth, 0, 0, 0, 0, 0, 0, MANUAL_startMeth, OFF_clockErr ), FlexArm(), initialJointPosition(2), Zero(2), desJtPosition(2), jointCommand(2), jointPosition(2), controlOut(2), error(2), Frequency(10)

int i, keepTrying_i = TRUE, retVal_i;
double temp;

if((fname=fopen("/uO/projects/Prismatic/dataFiles/BodeExp.dat", "w+")) == NULL)
  printf("fopen failed

desJtPosition[ROTARY]=0;
desJtPosition[PRISMATIC]=0;
// Create the compensator object
compensatorR_ap = new Comp( "././setupFiles/BodeServoComp.dat" ), 0);
compensatorP_ap = new Comp( "././setupFiles/BodeServoComp.dat" ), 0);
if (!compensatorR_ap||!compensatorP_ap)
  exit( ERROR );
// Read the sample frequency from the compensator for local use
sampleFreq_i = compensatorR_ap->SampleFreq_if();
if( sysClkRateSet( sampleFreq_i ) == ERROR )
  exit( ERROR );
if( sampleFreq_i )
  del_time_d = 1.0/((double) sampleFreq_i);
else
  del_time_d = 0.0;
// Initialize Robot object by passing base address
FlexArm.Init();
// Initialize other class members
tick_ul = 0;
double + elapsedRunTime_d = 0.0;
B0 = 0.0;
C0 = 0.0;

// Read in data related to the DFT
readDataFile setup_a( "/uO/projects/Prismatic/setupFiles/Bode.dat" );
setup_a.readNextParmAsInt_if( &BodeJoint, 1 );
setup_a.readNextParmAsDouble_if( &A0, 1 );
setup_a.readNextParmAsInt_if( &BodeExp.dat", &temp, 1);
Frequency[i] = temp;

// Start the controller
if( start_df() == ERROR )
  exit( ERROR );
// All is done. Print a message for the operator
logMsg( |/|

Bode Controller

METHOD NAME: doit_vf( void )
DESCRIPTION: Method to be called at a fixed period to perform the synchronous control.

void BodeController::doit_vf( void )
{
  int i,;
double j;
  double Ts, decay;
  Ts = del_time_d;
  double sampleFreq_d = 1/Ts;
  // Update loop related variables
  elapsedRunTime_d = del_time_d * tick_ul; // tick_ul is in processClass
  // Read the analog inputs
  jointPosition = FlexArm.GetJointPosition();
  if(tick_ul == 1)
    initialJointPosition = jointPosition;
  // Start off by moving to home position
  if( elapsedRunTime_d < timeHome_Cd )
    error = initialJointPosition-jointPosition;

Bode.C
else
decay=1.0-exp(-{elapsedRunTime_d-0.25*timeHome_Cd)/5.0);
error=(initialJointPosition+
decay*(desJtPosition-initialJointPosition) }
-jointPosition;
}
else
if(FREQ_COMPLETE == TRUE)

FREQ_COMPLETE = FALSE;
if(FIRST == TRUE)

FIRST=FALSE;
FreqIndex=0;
else

// Compute the magnitude and phase before resetting constants
Magnitude = (2/double(NumDataPoints))*sqrt(B0*B0+C0*C0)/A0;
Phase = 180.0*atan2(C0,B0)/3.14159265;

// Write results to a file
fprintf(fname,"%6.41f %3.11f %6.41f %6.41f %7.41f
",
A0, Frequency(FreqIndex), Magnitude, Phase, elapsedRunTime_d);
printf("nFreq=%3.11f Mag=%6.41f Phase=%6.41f Time=%4.21f
",
Frequency(FreqIndex), Magnitude, Phase,elapsedRunTime_d);
// Increment to the next frequency and cycle back to first freq. if
// the index exceeds the number of frequencies investigated
FreqIndex++; if(FreqIndex >= NumOfFreq)
FreqIndex=0;
}
// Compute the number of data points necessary to create ten cycles
// at the selected frequency and convert to rad/sec.
NumDataPoints=int(20*(sampleFreq_d)/Frequency(FreqIndex));
// Reset all necessary counters
DataPoint=0;
tick_ul=0;
elapsedRunTime_d=0;
B0 = 0;
C0 = 0;
// Reset the initial joint position
initialJointPosition = FlexArm.GetJointPositionO ;
if(DataPoint >= NumJoint)
FREQ_COMPLETE=TRUE;
}
if( !(tick_ul %50) )
printf("error=%6.41f %6.41f B0=%6.41f C0=%6.41f joint=%ld time=%4.11f\n", error[ROTARY],error[PRISMATIC],B0,C0,BodeJoint,elapsedRunTime_d);
if((compensatorR_ap->Next(error[ROTARY],&controlOut[ROTARY])!=1) ||
(compensatorP_ap->Next(-1.0*error[PRISMATIC],&controlOut[PRISMATIC])!= 1))
jointCommand=Zero;
else
jointCommand=controlOut;
jointCommand[ROTARY] = 0.02*error[ROTARY];
jointCommand[PRISMATIC] = -0.02*error[PRISMATIC];
// Write the analog outputs
FlexArm.SetCommand(jointCommand);
// Embedded sccs id string:
static char sccs_Bode_H[]="@(#>Bode.H 1.1";

#include <IP-padc.H>
#include <IP-dac.H>
#include <IP-dig24.H>
#include <processClass.H>
#include "compensator.H"
#include "Robot.H"
#include "matrix.H"

class BodeController : processClass
{
    public:
        BodeController( void );
        ~BodeController( void )
        {
            if( compensatorP_ap ) delete compensatorP_ap;
            if( compensatorR_ap ) delete compensatorR_ap;
            if( startTaskId_i ) startTaskId_i = 0;
            if( terminationSem_a )
            {
                semDelete( terminationSem_a );
                terminationSem_a = (SEM_ID) NULL;
            }
            printf("\nBodeController Destroyed..\n");
        }
    private:
        Robot * FloArm;
        double del_time_d, omega, Magnitude, Phase, A0, B0, C0;
        DFTCount, sampleFreq_d, elapsedRunTime_d;

       ummies timeHome_Cd = 40.0; // Seconds
        double biasCalcTime_Cd = 5.0; // Seconds
        int sampleFreq_i, FreqIndex, NumOfFreq, BodePoint,
            NumOfDataPoints;

        // Path and Control Vectors
        ColVector initialJointPosition;
        ColVector Zero;
        ColVector desJntPosition;
        ColVector jointCommand;
        ColVector jointPosition;
        ColVector error;
        ColVector controlOut;
        ColVector Frequency;

        // Pointer to a compensator object
        Comp * compensatorR_ap; // jfjansen added 8-29-95
        Comp * compensatorP_ap; // jfjansen added 8-29-95

        // Methods
        void doit_vf( void );
    };

    #ifndef BODE_H
    #define BODE_H

    #define MAX_NUMBER_OF_POINTS 10; // maximum number of points for a path

    int startTaskId_i = 0;
    SEM_ID terminationSem_a = (SEM_ID) NULL;

    // C++ includes
    #include <IP-padc.H>
    #include <IP-dac.H>
    #include <IP-dig24.H>
    #include <processClass.H>
    #include "compensator.H"
    #include "Robot.H"
    #include "matrix.H"

    // Path and Control Vectors
    ColVector initialJointPosition;
    ColVector Zero;
    ColVector desJntPosition;
    ColVector jointCommand;
    ColVector jointPosition;
    ColVector error;
    ColVector controlOut;
    ColVector Frequency;

    // Pointer to a compensator object
    Comp * compensatorR_ap; // jfjansen added 8-29-95
    Comp * compensatorP_ap; // jfjansen added 8-29-95

    // Methods
    void doit_vf( void );
};
#endif
/*
 * Oak Ridge National Laboratory
 * Robotics and Process Systems Division
 * U. S. Government internal use only
 *
 * FILE: Robot.H
 * AUTHOR: Lonnie Love
 * VERSION: %I%
 * Modified: %D %U%
 * Description:
 *
 * HISTORY:
 * # Date    By      Comment
 * --------- -------- ----------------
 * 1.0      05/10/96 Initial file creation.
 */

#ifndef ROBOT_H
#define ROBOT_H

enum actuators
{
  ROTARY,
  PRISMATIC,
  NUM_JOINTS
};

/* Embedded sccs id string: */
static char sccs_Robot_H[] = "%W%";

// C++ includes
#include "IP-padc.H"
#include "IP-dac.H"
#include "IP-dig24.H"
#include "processClass.H"
#include "matrix.H"
#include "vector.H"

class Robot
{
  public:
    Robot(void);
    ~Robot() { // Set the DAC outputs to zero...
      for (int i=0; i<(int)NUM_ANALOG_OUTPUTS_a; i++)
        dac_l_p->write_analogval(anOutChanMap_aa[i], analogDAC_BIAS_Cd[i]);
      if (dig24_l_p) delete dig24_l_p;
      if (padc_l_p) delete padc_l_p;
      printf("Robot: destroyed Robot object\n");
    }
    void Init(void);
    ColVector & GetJointPosition(void);
    ColVector & GetTrueTipPosition(void);
    ColVector & CalcDesJointPosition(const ColVector & tipPosition);
    ColVector & CalcTipPosition(const ColVector & jtPosition);
    void SetCommand(const ColVector & cmd);
};

private:
  ColVector JointPosition;
  ColVector DesJointPosition;
  ColVector TipPosition;
  ColVector TrueTipPosition;
  ColVector TipDeflection;
  ColVector Command;
  const int DOF = 2;
  const double pi = 3.1415926;
  const double PI = 3.1415926;

enum analogInputs
{
  NUM_ANALOG_INPUTS_a,
  // 3 channels used by John's manAmp
  HUMAN_FORCE_CHAN_a,
  LOAD_FORCE_CHAN_a,
  LOAD_POSITION_CHAN_a,
  // Next 2 channels are joint position
  FLEXIBLE_ROT_a,
  FLEXIBLE_PRIS_a,
  NUM_ANALOG_INPUTS_a
};

enum analogOutputs
{
  LOAD_COMMAND_FORCE_CHAN_a,
  FLEXIBLE_ROT_DRIVE,
  FLEXIBLE_PRIS_DRIVE,
  NUM_ANALOG_OUTPUTS_a
};

enum digitalInputs
{
  DEADMAN_SWITCH_CHAN_a,
  NUM_DIGITAL_INPUTS_a
};

enum digitalOutputs
{
  ENABLE_SERVO_VALVE_CHAN_a,
  DEBUG_TIMER_CHAN_a,
  NUM_DIGITAL_OUTPUTS_a
};

// Pointers to I/O objects
PADC_class * padc_l_p;
DAC_class * dac_l_p;
DIG24_class * dig24_l_p;

// Arrays for mapping I/O channels
int anInChanMap_aa[NUM_ANALOG_INPUTS_a];
dac_l_p->write_analogval(anOutChanMap_aa[i], analogDAC_BIAS_Cd[i]);
if (dig24_l_p) delete dig24_l_p;
if (padc_l_p) delete padc_l_p;
printf("Robot: destroyed Robot object\n");
}
void Init(void);
ColVector & GetJointPosition(void);
ColVector & GetTrueTipPosition(void);
ColVector & CalcDesJointPosition(const ColVector & tipPosition);
ColVector & CalcTipPosition(const ColVector & jtPosition);
void SetCommand(const ColVector & cmd);
#endif /* ROBOT_H */
Robot.C

*embedded id string: */
static char sccs_Robot_C[] = "%W%";

#include "Robot.H"
define VIPC610_VMEBUS_BASE_ADDR (0x6000)

extern "C"
{
#include <vxWorks.h>
#include <logLib.h>
#include <sysLib.h>
#include <taskLib.h>
#include <semLib.h>
#include <math.h>
#include <fioLib.h>
#include <vme.h>
}

METHOD NAME: Robot()
DESCRIPTION: Constructor method
Robot::Robot(void) : JointPosition(2), DesJointPosition(2), TipPosition(2), 
TrueTipPosition(2), TipDeflection(2),
{
logMsgl "Robot: Constructed Robot object\n",0,0,0,0,0,0);
}

METHOD NAME: Init()
DESCRIPTION: Initializes all drivers
void Robot::Init(void)
{
int retVal_i;
char * local_base_addr_cp;
retVal_i = sysBusToLocalAdrs( VME_AM_SUP_SHORT_IO, 
(char *) VIPC610_VMEBUS_BASE_ADDR, 
&local_base_addr_cp );
if( retVal_i == ERROR )
exit( ERROR );

// Create and setup the IP-DAC object
dac_l_p = new DAC_class( (int *) (local_base_addr_cp + IP_A_IO_OFFSET),
(unsigned char) 0x41 );
if(!dac_l_p)
exit( ERROR );

// Map the DAC channels to analogOutputs for convenient access
anOutChanMap_aa[ (int) LOAD_COMMAND_FORCE_CHAN_a ] = DAC_class::chan_1;
anOutChanMap_aa[ (int) FLEXIBLE_NOT_DRIVE ] = DAC_class::chan_2;
anOutChanMap_aa[ (int) FLEXIBLE_PRIS_DRIVE ] = DAC_class::chan_3;

// Initialize DAC bias values
analogDAC_BIAS_C[ FLEXIBLE_NOT_DRIVE ] = 0.000;
analogDAC_BIAS_C[ FLEXIBLE_PRIS_DRIVE ] = 0.316;

// Setup the DAC channels,
for(int i=0; i<NUM_ANALOG_OUTPUTS_a; i++)
dac_l_p->set_chnl( anOutChanMap_aa[i],
DAC_class::minusl0_to_plusl0 );

// Create and setup IP-PADC object
padc_l_p = new PADC_class( (int *) (local_base_addr_cp+IP_B_IO_OFFSET) );
if(!padc_l_p)
exit( ERROR );

// Map the PADC channels to the analogInputs array for convenient access
anInChanMap_aa[ (int) HUMAN_FORCE_CHAN_a ] = PADC_class::CH1;
anInChanMap_aa[ (int) LOAD_FORCE_CHAN_a ] = PADC_class::CH2;
anInChanMap_aa[ (int) LOAD_POSITION_CHAN_a ] = PADC_class::CH3;
anInChanMap_aa[ (int) FLEXIBLE_ROT_CHAN_a ] = PADC_class::CH4;
anInChanMap_aa[ (int) FLEXIBLE_PRIS_CHAN_a ] = PADC_class::CH5;

// Setup the PADC channels. No need to call calibratePadc_vf,
// given it's constructor already
for( i=0; i<NUM_ANALOG_INPUTS_a; i++ )
{
padc_l_p->set_chnl_vf( anInChanMap_aa[i],
PADC_class::X1, PADC_class::DIF );
switch( i )
{
case HUMAN_FORCE_CHAN_a:
analogInScaleFactor_da[i] = 10.0; // Lbs/Volt
break;
case LOAD_FORCE_CHAN_a:
analogInScaleFactor_da[i] = 100.0; // Lbs/Volt
break;
case LOAD_POSITION_CHAN_a:
analogInScaleFactor_da[i] = 2.1; // inches/volt
break;
case FLEXIBLE_ROT_CHAN_a:
analogInScaleFactor_da[i] = 45.0; // jfj
break;
case FLEXIBLE_PRIS_CHAN_a:
analogInScaleFactor_da[i] = 6.0; // jfj
break;
}
Listing for Lonnie Love

ColVector & Robot::GetTrueTipPosition(void)
{
    return(TrueTipPosition);
}

ColVector & Robot::CalcTipPosition(const ColVector & tipPosition)
{
    double x = tipPosition[0];
    double y = tipPosition[1];
    // In inches
    DesJointPosition[PRISMATIC] = 36.0 - sqrt(x*x+y*y);
    // In degrees
    DesJointPosition[ROTARY] = -(180/PI)*atan2(x, y);
    return(DesJointPosition);
}

ColVector & Robot::GetTipDeflection(void)
{
    return(TipDeflection);
}

ColVector & Robot::GetTrueTipPosition(void)
{
    return(TrueTipPosition);
}

ColVector & Robot::GetJointPosition(void)
{
    for (int i=0; i<(int)NUM_ANALOG_INPUTS; i++)
    {
        padc_l_p->read_analog_val_v£ (anInVals_da+i, anInChanMap_aa[i]);
        anInVals_da[i] *= analogInScaleFactor_da[i];
    }
    // Map to JointPosition vector
    JointPosition[PRISMATIC] = anInVals_da[PRISMATIC];
    JointPosition[ROTARY] = anInVals_da[ROTARY];
    return(JointPosition);
}

ColVector & Robot::GetTipDeflection(void)
{
    return(TipDeflection);
}

ColVector & Robot::GetTrueTipPosition(void)
{
    return(TrueTipPosition);
}

ColVector & Robot::GetJointPosition(void)
{
    for (int i=0; i<(int)NUM_ANALOG_INPUTS; i++)
    {
        padc_l_p->read_analog_val_v£ (anInVals_da+i, anInChanMap_aa[i]);
        anInVals_da[i] *= analogInScaleFactor_da[i];
    }
    // Map to JointPosition vector
    JointPosition[PRISMATIC] = anInVals_da[PRISMATIC];
    JointPosition[ROTARY] = anInVals_da[ROTARY];
    return(JointPosition);
}

METHOD NAME: CalcDesJointPosition
DESCRIPTION: Does the inverse kinematics on the tip position passed to the function.
ColVector & Robot::CalcDesJointPosition(const ColVector & tipPosition)
{
    double x = tipPosition[0];
    double y = tipPosition[1];
    // In inches
    DesJointPosition[PRISMATIC] = 36.0 - sqrt(x*x+y*y);
    // In degrees
    DesJointPosition[ROTARY] = -(180/PI)*atan2(x, y);
    return(DesJointPosition);
}

METHOD NAME: GetJointPosition
DESCRIPTION: Reads A/D for joint data and puts in JointPosition vector as well as returns the results in a vector.
ColVector & Robot::GetJointPosition(void)
{
    for (int i=0; i<(int)NUM_ANALOG_INPUTS; i++)
    {
        padc_l_p->read_analog_val_v£ (anInVals_da+i, anInChanMap_aa[i]);
        anInVals_da[i] *= analogInScaleFactor_da[i];
    }
    // Map to JointPosition vector
    JointPosition[PRISMATIC] = anInVals_da[PRISMATIC];
    JointPosition[ROTARY] = anInVals_da[ROTARY];
    return(JointPosition);
}

METHOD NAME: GetTrueTipPosition
DESCRIPTION: Uses joint and deformation information to estimate the true tip position of the robot.
/*
 *  File: FlexController.H
 *  Author: Lonnie J Love
 *  Version: 1.0
 *  Modified: 19 Jan 1996 09:01:34
 */

#include <IP-padc.H>
#include <IP-dac.H>
#include <IP-dig24.H>
#include <processClass.H>
#include "compensator.H"
#include "Robot.H"
#include "matrix.H"

class FlexController : processClass
{
public:
  FlexController( void );
  ~FlexController( void )
  {
    if ( compensator_ap ) delete compensator_ap;
    if ( compensatorR_ap ) delete compensatorR_ap;
    if ( compensatorP_ap ) delete compensatorP_ap;
    if ( compensatorFlexRot_ap ) delete compensatorFlexRot_ap;
    if ( compensatorFlexPris_ap ) delete compensatorFlexPris_ap;
    if ( startTaskId_i ) startTaskId_i = 0;
    if ( terminationSem_a )
    {
      semDeletef terminationSem_a );
      terminationSem_a = (SEM_ID) NULL;
    }
    printf("\nFlexController Destroyed.,\n")
  };

  void setControllerInitialConditions_vf( void );
  void doit_vf( void );

private:
  Robot
  double del_time_d,
  pathRunTime_d,
  elapsedRunTime_d;
  int goneHomeMsgFlag_i,
  deadmanSwitchTimer_i,
  biasCalcMsgFlag_i,
  operatingMsgFlag_i,
  sampleFreq_i;
  
  const double deadmanDelay_Cd = 1.0; // Seconds
  const double timeHome_Cd = 40.0; // Seconds
  const double runtime_Cd = 20.0; // Seconds
  const double biasCalcTime_Cd = 5.0; // Seconds
  const double pathPause = 2.0; // Seconds
  const double startupTime_Cd = 5.0; // Seconds
  
  double stopTime_Cd;

  // Path and Control Vectors
  CoIVector initialJointPosition;
  CoIVector desJtPosition;
  CoIVector desTipPosition;
  CoIVector jointCommand;
  CoIVector jointPosition;
  CoIVector tipPosition;
  CoIVector finalTipPosition;
  CoIVector Xdes;
  
  error;
  CoIVector controlOut;
  CoIVector XFilter;
  Matrix Path;
  int pathNumberOfPoints, numPoints,
  LineIndex, PointIndex;

  // Pointer to a compensator object
  Comp * compensatorAp;
  Comp * compensatorP_ap; // jjfjansen added 6-22-95
  Comp * compensatorV_ap; // jjfjansen added 6-29-95
  Comp * compensatorR_ap; // jjfjansen added 6-29-95
  Comp * compensatorPris_ap; // jjfjansen added 6-29-95
  Comp * compensatorFlexRot_ap; // ljl added 4-17-96
  Comp * compensatorFlexPris_ap; // ljl added 4-17-96

  
  // Methods
  void setControllerInitialConditions_vf( void );
  void doit_vf( void );

  #endif

};
Listing for Lonnie Love

FILE: FlexController.C
AUTHOR: Lonnie J. Love
VERSION: 1.4
MODIFIED: 19 Jan 1996 09:00:18
DESCRIPTION: Kick off the task to create and maintain the human amp controller object

HISTORY:

Date     By            Comment
-------   --------      ---------------------
1.5       06/03/96     LJL - Changed to FlexController Class
1.4       08/09/95     PMR - Broke program into controller and new Robot class
1.3       08/09/95     PMR - Removed HUMAN_MODELING_TEST stuff
1.2       07/05/95     PMR - Added load cell bias voltage monitor
1.1       06/15/95     PMR - Full humanAmp capabilities demonstrated in both NORMAL and BODE modes
1.0       06/12/95     PMR - Initial file creation.

FILE LINE COMPLETE *fname = 
true;
false;
true;
false;
false;
true;

FUNCTION NAME: startFlex_vf()
DESCRIPTION: Kick off the task to create and maintain the human amp controller object

void startFlex_vf (void)
{
if(startTaskId_i | terminationSem_a)
    logMsg( "Controller already running\n", 0, 0, 0, 0, 0, 0, 0);
else
    startTaskId_i = taskSpawn("tHAStart",
          9, VX_FP_TASK, 5000,
          (FUNCPT) FlexTask_if,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          PATH_COMPLETE = FALSE;
LINE_COMPLETE = TRUE;
}

FUNCTION NAME: getPath_if()
DESCRIPTION: Task which is entered by user and reads in Path.dat

int getPath_if (void)
{
    // Set path flag. This will cause FlexController::getPath() method to
    // execute in FlexController::doit()
    PATH_SET = TRUE;
    return(OK);
}

FUNCTION NAME: FlexTask_if()
DESCRIPTION: Task which creates and maintains the Flexure controller

int FlexTask_if (void)
{
    // Create the semaphore used to terminate this task
    terminationSem_a = semCreate(0, SEM_EMPTY);
    // Create the instance of the human amplifier controller
    FlexController controller_a;
    printf("Built FlexController\n\n");
    // Wait for the termination sem to be given by the stopFlex_vf func.
    // When it is given, delete the sem and clear the task ID buffer, then
    // return (which terminates the controller)
    semTake( terminationSem_a, WAIT_FOREVER );
    semDelete( terminationSem_a );
}

// C includes
extern "C"
{
#include <vxWorks.h>   // For OK/ERROR
#include <logLib.h>    // For logMsg()
#include <stdio.h>     // For printf()
#include <sysLib.h>    // For sysClkRateSet()
#include <taskLib.h>   // For taskDelay(), tasklock(), taskunlock()
#include <semLib.h>    // For semaphore calls
#include <math.h>      // For ldexp()
#include <fioLib.h>    // For fioReadString
#include <vme.h>       // For.ctime

void startFlex_vf (void);
void stopFlex_vf (void);
int FlexTask_if (void);
int getPath_if (void);

// C++ includes
#include "FlexController.H"
#include "Robot.H"
#include "traj.H"
#include <readDataFile.H>

// Local macros
int PATH_SET = TRUE;
int PATH_COMPLETE_MESSAGE = FALSE;
int PATH_COMPLETE = FALSE;

// Command-line-callable functions

// For OK/ERROR
// For logMsg()
// For printf()
// For sysClkRateSet()
// For taskDelay(), tasklock(), taskunlock()
// For semaphore calls
// For ldexp()
// For fioReadString
// For ct ime

int LINE_COMPLETE = true;
FILE *fname;
terminationSem_a = (SEM_ID) NULL;
startTaskId_i = 0;
printf( "\nFlexTask_if: Stopping Flexure controller\n", 0,0,0,0,0,0 );
return(OK);

FUNCTION NAME: stopFlex_vf
DESCRIPTION: Kill off the controller

void stopFlex_vf( void )
{
    if( startTaskId_i && terminationSem_a
        semGive( terminationSem_a );
}

METHOD NAME: FlexController
DESCRIPTION: Constructor method

FlexController::FlexController(void )
{
    int i,
    keepTrying_i = TRUE,
    retVal_i;

    // Create the compensator object
    compensator_ap=new Comp("/uO/projects/Prismatic/setupFiles/ServoComp.dat", 0 );
    compensatorP_ap=new Comp("/uO/projects/Prismatic/setupFiles/ServoPComp.dat", 0 );
    compensator_ap = new Comp( "/uO/projects/Prismatic/setupFiles/ServoComp.dat", 0 );
    compensatorFlexRot_ap=new Comp("/uO/projects/Prismatic/setupFiles/FlexComp.dat ", 0 );
    compensatorFlexPris_ap=new Comp("/uO/projects/Prismatic/setupFiles/FlexComp.da ");

    if (!compensator_ap) || (!compensatorFlexRot_ap) || (!compensatorFlexPris_ap) || (compensator_ap) || (compensatorflex Rot_ap) )
        exit( ERROR );
    // Read the sample frequency from the compensator for local use
    sampleFreq_i = compensator_ap->SampleFreq_if();
    // Set the rate of the CPU's system clock (ticks per second)
    if ( sysClkRateSet( sampleFreq_i ) == ERROR )
        exit( ERROR );
    // Set the frequency of controller looping
    if ( changeProcessFrequency_if( sampleFreq_i ) == ERROR )
        exit( ERROR );
    if( sampleFreq_i )
        del_time_d = 1.0/(double) sampleFreq_i;
    else
del_time_d = 0.0;

    // Initialize Robot object by passing base address
    FlexArm.Init();
    // Initialize other class members
tick_ul = 0;
    deadManSwitchTimer_i = (int) deadManDelay_Cd * sampleFreq_i;
double elapsedRunTime_d = 0.0;

    // Load path variables if appropriate (added by ljl - 4/16/96)
    if(PATH_SET == TRUE)
        getPathO;

    // Print out results
    printf("\n\nPath Parameters. . .\n") ;
    for (i=0;i<pathNumberOfPoints ;i++)
        printf("\nXf=[%4.21f %4.21f] Vmax=%4.21f Amax=%4.21f\n",
Path(i)[0],Path(i)[1],Path(i)[2],Path(i)[3]);

    if( start_if() == ERROR )
        exit( ERROR ) ;
    // All is done. Print a message for the operator
    logMsg( "\n\n\n\n", 0,0,0,0,0,0 );
    logMsg( "| |
", 0,0,0,0,0,0 ) ;
    logMsg( "III Construction complete. Controller is running | | |
", 0,0,0,0,0,0 );
    logMsg( " | 1 


", 0,0,0,0,0,0 ) ;
    return(OK);
}

// Method to initialize the compensator
int initializeComp( void )
{
    int i;
    for (i=0;i<pathNumberOfPoints ;i++)
        printf("\n\nPath Parameters. . .\n") ;
    return(OK);
}

// Method to start the controller
int startController( void )
{
    int i,
    keepTrying_i = TRUE,
    retVal_i;

    // Create the compensator object
    compensator_ap=new Comp("/uO/projects/Prismatic/setupFiles/ServoComp.dat", 0 );
    compensatorP_ap=new Comp("/uO/projects/Prismatic/setupFiles/ServoPComp.dat", 0 );
    compensator_ap = new Comp( "/uO/projects/Prismatic/setupFiles/ServoComp.dat", 0 );
    compensatorFlexRot_ap=new Comp("/uO/projects/Prismatic/setupFiles/FlexComp.dat ", 0 );
    compensatorFlexPris_ap=new Comp("/uO/projects/Prismatic/setupFiles/FlexComp.da ");

    if (!compensator_ap) || (!compensatorFlexRot_ap) || (!compensatorFlexPris_ap) || (compensator_ap) || (compensatorflex Rot_ap) )
        exit( ERROR );
    // Read the sample frequency from the compensator for local use
    sampleFreq_i = compensator_ap->SampleFreq_if();
    // Set the rate of the CPU's system clock (ticks per second)
    if ( sysClkRateSet( sampleFreq_i ) == ERROR )
        exit( ERROR );
    // Set the frequency of controller looping
    if ( changeProcessFrequency_if( sampleFreq_i ) == ERROR )
        exit( ERROR );
    if( sampleFreq_i )
        del_time_d = 1.0/(double) sampleFreq_i;
    else
del_time_d = 0.0;

    // Initialize Robot object by passing base address
    FlexArm.Init();
    // Initialize other class members
tick_ul = 0;
    deadManSwitchTimer_i = (int) deadManDelay_Cd * sampleFreq_i;
double elapsedRunTime_d = 0.0;

    // Load path variables if appropriate (added by ljl - 4/16/96)
    if(PATH_SET == TRUE)
        getPathO;

    // Print out results
    printf("\n\nPath Parameters. . .\n") ;
    for (i=0;i<pathNumberOfPoints ;i++)
        printf("\nXf=[%4.21f %4.21f] Vmax=%4.21f Amax=%4.21f\n",
Path(i)[0],Path(i)[1],Path(i)[2],Path(i)[3]);

    if( start_if() == ERROR )
        exit( ERROR ) ;
    // All is done. Print a message for the operator
    logMsg( "\n\n\n\n", 0,0,0,0,0,0 );
    logMsg( "| |
", 0,0,0,0,0,0 ) ;
    logMsg( "III Construction complete. Controller is running | | |
", 0,0,0,0,0,0 );
    logMsg( " | 1 


", 0,0,0,0,0,0 ) ;
    return(OK);
}
METHOD NAME: getPath ()
DESCRIPTION: Method to read Path.dat file and store results in Path matrix

```c
int FlexController::getPath(void)
{
    double temp;
    // open up new file for saving data (closed at end of path)
    if((fname=fopen("/uO/projects/Prismatic/dataFiles/PrismExp.dat", "w+"))==NULL)
        printf("fopen failed\n");
    readDataFile setup_a( "/uO/projects/Prismatic/setupFiles/Path.dat") ;
    setup_a.readNextParmAsInt_if( SpathNumberOfPoints, 0);
    printf("\nNumber of Points %ld\n",pathNumberOfPoints);
    for(int i=0;i<pathNumberOfPoints;i++)
    {
        setup_a.readNextParmAsDouble_if( &temp, 0);
        Path[i][0]=temp; // final X
        setup_a.readNextParmAsDouble_if( &temp, 0);
        Path[i][1]=temp; // final Y
        setup_a.readNextParmAsDouble_if( &temp, 0);
        Path[i][2]=temp; // max velocity
        setup_a.readNextParmAsDouble_if ( fitemp,
                                          &temp, 0);
        Path[i][3]=temp; // max acceleration
    }
    setup_a.closeSetupFile_if();
    // Initialize the starting point at the current arm position
    initialJointPosition=FlexArm.GetJointPosition();
    LineIndex=0;
    PointIndex=0;
    tick_ul=0;
    PATH_COMPLETE = FALSE;
    LINE_COMPLETE = TRUE;
    return(OK);
}
```

METHOD NAME: doit_vf()
DESCRIPTION: Method to be called at a fixed period to perform the
synchronous control.

```c
void FlexController::doit_vf( void )
{
    int i,
        j,
        ratVal_i;
    double desVel,
            maxAcc,
            Ts,
            decay;
    ColVector XFiltdes(2);
    static MinTimeTrajectory Line(2); // use minimum time trajectories on path
    Ts = del_time_d;
    if( (PATH_SET==TRUE) & (PATH_COMPLETE == TRUE) )
    {
        taskLock();
        printf("\nset Path in doit()\n");
        getPath();
        taskUnlock();
        PATH_SET = FALSE;
    }
```
Listing for Lonnie Love

```
finalTipPosition[0]=Path[LineIndex+1][0];
initialTipPosition[1]=Path[LineIndex+1][1];
finalTipPosition[1]=Path[LineIndex+1][1];
desVel=Path[LineIndex+1][2];
maxAcc=Path[LineIndex+1][3];
Line.Reset(initialTipPosition,finalTipPosition,desVel,maxAcc,Ts);
PointIndex=0;
LINE_COMPLETE=FALSE;
printf("\nLineIndex=%d NumPoints=%d\n",LineIndex,NumPoints);
}
desTipPosition=Line.Update(PointIndex);
PointIndex++;
if(PointIndex==NumPoints-1)
{
    LineIndex++;
    LINE_COMPLETE=TRUE;
}
if(LineIndex>=pathNumberOfPoints-1)
{
    stopTime_Cd = elapsedRunTime_d;
    printf("\n");
    PATH_COMPLETE=TRUE;
    PATH_COMPLETEMESSAGE=TRUE;
    // Inverse Kinematics to get desired joint values
    Xdes=FlexArm.CalcDesJointPosition(desTipPosition);
    // Run the filter here to flush out any transients.
    compensatorFlexRot_ap->Next(Xdes[ROTARY], SXFiltdes[ROTARY]);
    compensatorFlexPris_ap->Next(Xdes[PRISMATIC], SXFiltdes[PRISMATIC]);
    // Not running filter yet
    error=Xdes-jointPosition;
    if(!(tick_ul %10))
    {
        printf("Tip=%4.21f %4.21f Joint=%4.21f %4.21f\r", tipPosition[0],tipPosition[1],jointPosition[ROTARY], jointPosition[PRISMATIC]);
    }
    else
    {
        printf(fname,
            "%6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f
            jointPosition[0], jointPosition[1],
            Xdes[ROTARY], Xdes[PRISMATIC],
            tipPosition[0],tipPosition[1],
            desTipPosition[0],desTipPosition[1],elapsedRunTime_d);
    }
}
else
{
    error=Xdes-jointPosition;
    printf(fname,
        "%6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f %6.41f
        jointPosition[0], jointPosition[1],
        Xdes[ROTARY], Xdes[PRISMATIC],
        tipPosition[0],tipPosition[1],
        desTipPosition[0],desTipPosition[1],elapsedRunTime_d);
    if( elapsedRunTime_d < (biasCalcTime_Cd + timeHome_Cd) )
    {
        if((compensatorR_ap->Next(error[ROTARY], &controlOut[ROTARY]) !=1) | |
            (compensatorP_ap->Next(-1.0*error[PRISMATIC], &controlOut[PRISMATIC]) != 1))
        {
            printf("error in jointCommand\r\n"),
            jointCommand=Zero;
        }
        else
        jointCommand=controlOut;
    }
    else
    {
        if((compensatorP_ap->Next(-1.0*error[PRISMATIC], &controlOut[PRISMATIC]) !=1) | |
            (compensatorR_ap->Next(error[ROTARY], &controlOut[ROTARY]) != 1))
        {
            printf("error in jointCommand\r\n"),
            jointCommand=Zero;
        }
        else
        jointCommand=controlOut;
    }
    // Write the analog outputs
    FlexArm.SetCommand(jointCommand);
}
```

---

### FlexController.C

**Method Name:** `setControllerInitialConditions_vf`

**Description:** Method to reset the controller's initial conditions.

```c
void FlexController::setControllerInitialConditions_vf( void )
{
    return;
}
```
Dynamic Accuracy Test
TITAN 7F and GAMMA 7F REMOTE MANIPULATOR SYSTEMS

Schilling Development, Inc. meets user requirements for seven-function remote manipulators with two highly dexterous and powerful servo-hydraulic Master Slave systems. The TITAN 7F and GAMMA 7F. Each are constructed primarily of 6-4 titanium and employ advanced electronic and mechanical design for use whenever manipulative tasks must be performed in locations or environments where man cannot safely or practically venture. Applications range from undersea to radioactive environments.

The TITAN 7F has acquired an impeccable reputation since its introduction in 1987 and is seeing service for a variety of commercial, scientific and military users. Typical tasks range from undersea salvage, maintenance and construction to ordnance handling and toxic cleanup.

Building upon the TITAN 7F's established record of reliability and performance, the GAMMA 7F provides for operation in radioactive environments. Through careful selection of radiation resistant materials, the GAMMA 7F is designed to tolerate an accumulated exposure of 10⁵ RAO gamma radiation. Now a standard, commercially proven product is available that eliminates costly development, rework costs and reliability concerns associated with custom designed equipment.

The TITAN 7F and GAMMA 7F are controlled by compact master arms that provide for comfortable and intuitive handling and operation. Each system has a hydraulic and control system designed to simplify and fluidize function with a repeating control loop giving the manipulators familiarity and accuracy.

FEATURES
- Available for underwater and terrestrial applications
- Microprocessor, servo controlled
- Dextorous and powerful
- 250 lb. payload at full arm extension
- Radiation hardened to 10⁵ RAO
- Oil hydraulic and silicone based fluid compatible
- Titanium construction
- Portable master controller that are simple to learn, easy to operate and require little space
- Compact and powerful three axis wrist assembly
GENERAL DESCRIPTION
Mode of Operation: Spatially Correspondent
Input Device: Compact Master Control Arm
Number of Functions: Seven
Power System: (TITAN 7F) Oil Hydraulic, (GAMMA 7F) Multi Fluid Compatible

DIMENSIONS AND SPECIFICATIONS
SLAVE ARM
- Maximum Reach: 78 inches
- Lift capacity at Full Extension: 250 lbs.
- Jaw Capacity: 4.0 inches (standard)
- Jaw Closure Force: 350 lbs. max.
- Weight in Air: 147.0 lbs.
- Weight in Water: 113.0 lbs.

MASTER CONSOLETTE
- Height: 10.0 inches
- Width: 6.0 inches
- Length: 19.0 inches
- Weight: 10.0 lbs.

SLAVE CONTROLLER ASSEMBLY
- Height: 4.0 inches
- Width: 7.5 inches
- Length: 16.0 inches
- Weight in Air: 27.0 lbs.
- Weight in Water: 14.5 lbs.

PERFORMANCE
<table>
<thead>
<tr>
<th>Hardware</th>
<th>Max. Slew Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waist Yaw</td>
<td>270° 90°/sec.</td>
</tr>
<tr>
<td>Shoulder Pitch</td>
<td>90° 90°/sec.</td>
</tr>
<tr>
<td>Elbow Pitch</td>
<td>120° 90°/sec.</td>
</tr>
<tr>
<td>Wrist Pitch</td>
<td>180° 400°/sec.</td>
</tr>
<tr>
<td>Wrist Yaw</td>
<td>180° 400°/sec.</td>
</tr>
<tr>
<td>Wrist Rotate</td>
<td>Slaved 270°</td>
</tr>
<tr>
<td></td>
<td>Continuous 0 to 55 rpm</td>
</tr>
<tr>
<td></td>
<td>Wrist Torque 70 ft. lbs. (peak)</td>
</tr>
</tbody>
</table>

HYDRAULIC REQUIREMENTS
3000 psi - 3.0 gpm nominal

ELECTRICAL REQUIREMENTS
25 watts nominal powered by 120/240 VAC or 20-30 VDC

TELEMETRY REQUIREMENTS
RS-422 type media - Single twisted wire pair; RG-108 or equivalent

OPTIONS
Contact Schilling Development, Inc. for details.
Available in single and dual manipulator configurations.

Description and specifications are subject to change without notice. Contact Schilling Development for latest information.
1.2 TITAN 7F Description

The Schilling Development TITAN 7F is a high velocity, compact and lightweight, spatially correspondent manipulator system specifically designed for remote manipulation. The TITAN 7F has six degrees of freedom plus grip and is controlled by a master controller. Movements introduced at the master control arm by the operator are duplicated by the slave arm, maintaining the spatial correspondence between the master and the slave.

For the purposes of this chapter, the system can be viewed as three components: 1) the slave arm; 2) the slave controller; and 3) the master console, containing the master control arm and the master control electronics. The manipulator system is an engineered integration of mechanical assemblies, servo-hydraulics, and a microprocessor based position control system. Because the TITAN 7F is an integrated system, it is not possible to completely segregate the functions of the subsystems. Frequent cross-references will be made to the subsystems in the discussion that follows. See Figure

![Figure 1.1-Titan 7F Manipulator System and Major Assemblies](image-url)
Figure 8.1 System Overview
The Master Control Arm

Inner electronics to determine the positioning of the master control arm. The Master Control Arm Freeze button is located on the tip of the control arm. Deflecting the button toggles the FREEZE switch between OFF and ON settings. In this version of the master controller, the function of the FREEZE button is user defineable. The 6 DOF master control arm is shown in Figure 1.3.