A MODEL-FREE FINE POSITION CONTROL METHOD USING THE BASE-SENSOR: WITH APPLICATION TO A HYDRAULIC MANIPULATOR

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Abstract: Manipulators are often required to perform small amplitude, slow motions with very high precision. For hydraulic manipulators these fine motions are difficult to execute due to high nonlinear joint friction found in these systems. Poor tracking, stick-slip behavior, and large static position errors often occur. Current methods proposed to improve the performance of hydraulic manipulators require complex modeling and identification and often produce marginal results. Here, a control scheme based on feedback from a base-mounted force/torque sensor is presented. The theoretical background for the method is presented, and an easy to implement simplified form is developed, based on quasi-static equations. Experimental results for a Schilling Titan II industrial hydraulic manipulator performing fine-motion tasks under the simplified control algorithm are presented. It is shown that performance is significantly improved over traditional control methods. It is also shown that the control scheme is robust to changes in payload.

Keywords: Manipulator, Hydraulic Actuators, Position Control, Torque Control, Friction

1. INTRODUCTION

Hydraulic manipulators are frequently used in industrial applications requiring the manipulation of heavy payloads and the application of large forces. Such tasks are common in nuclear maintenance, undersea, and field applications. Hydraulic robots are attractive due to their high load carrying capacity (relative to typical electric motor-driven robots), but are often difficult to control due to higher joint friction and actuator nonlinearities.

This can be a problem in tasks that require a strong manipulator with high positional accuracy, such as in positioning of a large and heavy payload. The nozzle dam positioning problem in the maintenance of nuclear power plant steam generators is a typical example of such a task (Electricité de France, 1996). Small, slow motions may be needed in order to make fine adjustments of the payload position as it nears its target area. Thus, control schemes for industrial hydraulic manipulators are required that deliver precise, low-velocity positioning and are robust to changes in payload.

Classical PID control is most commonly used for hydraulic manipulators due to its simplicity and ease of implementation. No dynamic model of the actuators or manipulator is required, which is a significant factor for hydraulic systems, since modeling and identification of the nonlinear actuators is very complex (Habibi and Richards, 1994; Electricité de France, 1996).

While PID control can provide acceptable performance for some tasks with large amplitude and moderate-speed motions, it is often not able to meet the needs of tasks with low-speed, small motions,

where nonlinear joint effects (such as stiction) can dominate system performance (Armstrong, 1991). When low-speed, small motions are attempted while manipulating a large payload, performance may be degraded even further. The manipulator may exhibit stick-slip behavior or limit cycle oscillations. In some nuclear plant maintenance operations, PID control is so ineffective that it prohibits completion of even relatively simple tasks.

There are several existing approaches for improving fine motion manipulator performance. These approaches focus on friction compensation. However, they are hampered by one of the following factors. They require modeling of frictional behavior (Popovic, *et al*., 1994; Canudas de Wit, *et al*., 1996). Joint friction is very difficult to characterize, since it is highly variable with time, temperature, wear, and other factors. They can require the use of specially designed joint-torque sensors (Pfeffer, *et al*., 1989). These sensors are costly, complex, and have limited accuracy. Finally, some methods have been proposed that control only finite displacements, ignoring the trajectory tracking problem and thus making it difficult for them to produce smooth, slow motions (Popovic, *et al*., 1995). A discussion of friction compensation techniques can be found in (Morel and Dubowsky, 1996).

A simple control scheme that overcomes the above limitations has been developed and demonstrated on an electrical industrial robot (Morel and Dubowsky, 1996). This method utilizes feedback from a six-axis force/torque sensor mounted at the base of the manipulator, which is used to estimate the torque at each joint of the manipulator. The estimation process is based on Newton-Euler equations of successive rigid bodies. With an estimate of the joint torque, accurate joint torque control is possible. This leads to improved friction compensation, which in turn allows the execution of fine-motion tasks. This method is attractive due to the simplicity of its implementation and its excellent performance. It does not require models of the nonlinear actuator characteristics or joint friction, nor does it require the manipulator to be retrofitted with expensive and difficult-to-implement joint-torque sensors.

There is little discussion in the literature of fine motion control as applied to hydraulic manipulators. One recent position control method utilizes a nonlinear PI controller, with the integral term modified to include a term which is designed to detect the onset of stiction (Heinrichs, *et al*., 1996). This method is attractive due to its ease of implementation. However, the authors reported that performance was poorest for fine motions, where friction effects have large influence.

In this paper, the theoretical basis of the base-sensor joint-torque estimation algorithm is briefly reviewed.

It is then shown that if dynamic terms of the joint-torque estimation equations are neglected and gravity torque is assumed to be constant, the estimation equations become a series of computationally very simple force-moment transformations. This highly simplified form of the algorithm is then applied to an industrial hydraulic manipulator with very high joint friction, with a simple control architecture that utilizes a proportional compensator in an outer position loop and an integral compensator for the inner torque loop. The experimental results clearly demonstrate that excellent tracking performance during fine motion tasks is achievable with this simplified form of the algorithm. The control method does not require a model of the actuators or the friction, nor does it require knowledge of manipulator mass parameters. Measurements of joint velocity or acceleration are not necessary. The method is essentially model free.

2. ANALYTICAL BASIS OF THE METHOD

The generalized dynamic torque estimation equations used in the base-sensor control process are presented in (Morel and Dubowsky, 1996). Here, a simplified yet effective version of the equations is presented. The simplified equations are shown to be sufficient and effective for fine-motion control. The reduction is based on two assumptions. The first is that for small motions, the torque at the joints caused by gravity is essentially constant. The second is that for slow motions, the effects of manipulator dynamics are negligible.

In the general case, the wrench, W_b, exerted by the manipulator shown in Figure 1 on its base sensor can be expressed as the sum of two components:

$$W_b = W_g + W_d \qquad (1)$$

where W_g is the gravity component, and W_d is the component caused by manipulator motion. Note that the base sensor measures forces and torques corresponding to joint torques that are effectively transmitted to the manipulators links. Thus, friction does not appear in the measured wrench.

In the general algorithm, the gravity wrench is compensated for using the following model (Baker, 1992; West, *et al*., 1989):

$$W_d = W_b - W_g = W_b - \left(\begin{aligned} F_g &= \sum_{i=1}^{n} m_i g \\ M_g^{O_s} &= \sum_{i=1}^{n} O_s G_i \times m_i g \end{aligned} \right) \qquad (2)$$

where F_g and M_g° are the gravity force and moment at the center of the sensor O_S, respectively, m_i and G_i are the mass and the location of the center of mass of link i, respectively.
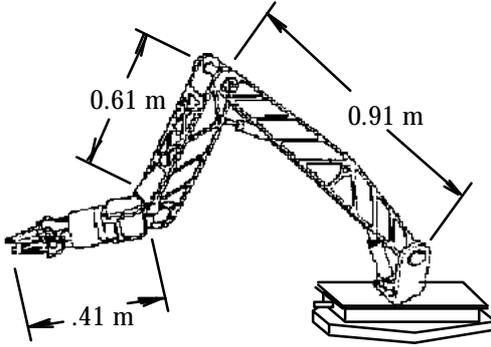

Fig. 1. Schilling Titan II on a force/torque sensor

In the general algorithm, the gravity wrench is computed for every manipulator configuration along a trajectory. In the fine-motion case, it is assumed that since the manipulator range of motion is small, the gravity wrench is essentially constant, and is set equal to the initial value measured by the base sensor. Hence, the complexity of computing the gravitational wrench, such as identification of link weights and a static manipulator model, is eliminated. If the joints of the manipulator move just a few degrees, errors in the gravitational terms are only a few percent.

Under this assumption, the Newton Euler equations of the first i links are:

$$\begin{cases} W_{0 \to 1} = -W_{base} \\ W_{1 \to 2} = W_{0 \to 1} - W_{d_1} \\ \quad\quad\quad \vdots \\ W_{i \to i+1} = W_{i-1 \to i} - W_{d_i} \end{cases} \quad (3)$$

where $W_{i \to i+1}$ is the wrench exerted by the link i on the link i+1 and W_{di} is the dynamic wrench for link i. The W_{di} term can be expressed at any point A in terms of the acceleration $\acute{V}_{Gi}$ of G_i, the angular acceleration $\acute{\omega}_i$ and the angular velocity ω_i:

$$W_{d\,i} = \begin{pmatrix} F_{d_i} = m_i \acute{V}_{G_i} \\ M_{d_i}^A = I_i \acute{\omega}_i + \omega_i \times I_i \omega_i + G_i A \times m_i \acute{V}_{G_i} \end{pmatrix} \quad (4)$$

The torque in joint i+1 is obtained by projecting the moment vector at O_i along z_i (see Figure 2):

$$\tau_{i+1} = -z_i^t \left[M_d^{O_i} + \sum_{j=1}^{i} \left(I_j \acute{\omega}_j + \omega_j \times I_j \omega_j + O_i G_j \times m_j \acute{V}_{G_j} \right) \right] \quad (5)$$

Where M_d is the dynamic moment component of the base wrench.

Analysis of this equation shows that for joints nearest to the base sensor with orthogonal axes of rotation, torque estimation equations that depend only on the measured base wrench can be written. However, for distal joints that have axes of rotation that are non-orthogonal to the axes of rotation of proximal links, dynamic terms must be included in the torque estimation equations. This requires knowledge of joint velocity and acceleration.

For the fine-motion case, it is assumed that the manipulator moves very slowly. In this case, W_d terms will generally be negligible. Hence, dynamic terms are treated as a disturbance. As a result, for slow, fine motions, only the measured wrench at the base is used to estimate the torque in joint i+1. The torque is estimated by projecting the base wrench at O_i along z_i (See Figure 2). This leads to:

$$\tau_{i+1} = -z_i^t \cdot W_{base}^{O_i} \quad (6)$$

A generalized form of Equation 6 can be written as:

$$\tau = A(q) \cdot W_{base}^{O_{sensor}} \quad (7)$$

Where τ is the vector of estimated joint torques and the matrix A is a function of joint positions and manipulator kinematic parameters. Thus, the method does not depend on measurements (or estimations) of the joint velocities or accelerations, estimates or models of masses or inertias of the links or the payload, or models of the actuator dynamics or friction, but only on joint positions, and the manipulator's kinematic parameters.
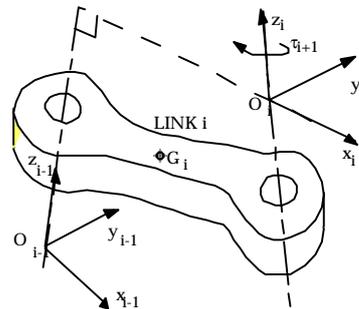

Fig. 2. Body-fixed coordinate frames for link i

3. CONTROLLER DESIGN

The position control scheme consists of an inner torque loop and an outer position loop, as shown in Figure 3. An inner loop integral compensator provides low-pass filtering, and zero steady-state

error. Previous theoretical and experimental work has shown that an integral compensator with a feedforward term provides the best torque control performance for a geared, DC motor-driven manipulator (Morel and Dubowsky, 1996; Vischer and Khatib, 1995). Similar linear analysis is less conclusive for the Titan II, due to its highly nonlinear characteristics at the operating range of interest. Experimentation has shown, however, that the selection of an inner loop integral compensator is effective for this system.
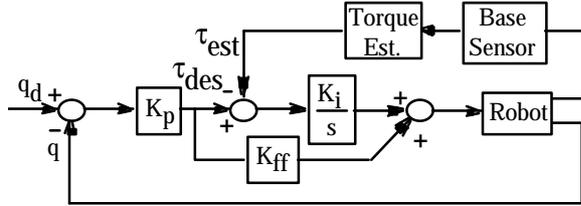

Fig. 3. Control System Architecture

A simple proportional controller is employed in the outer loop. A derivative term was not added (as in (Morel and Dubowsky, 1996)) due to the damping inherent in the system. This yields:

$$V_{out} = K_{ff}\tau_{des} + K_{int}\int_0^t (\tau_{des} - \tau_{est}) \qquad (8)$$

with

$$\tau_{des} = K_p(q_d - q) \qquad (9)$$

Equation (6), when applied to the Titan II, yields the following expression for the first three joints (see Figure 4 for Titan II frame assignments):

$$\begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & -s1 & c2 & 0 \\ a2c1s2 & -a2s1s2 & -a2c2 & -s1 & c2 & 0 \end{pmatrix} \begin{pmatrix} F_b \\ M_b \end{pmatrix} \quad (10)$$

Note that the torque estimation equations depend only on the manipulator joint positions, the measured base wrench, and the manipulator's kinematic parameters. These estimation equations are computationally very simple, and for the case of the Titan II requires knowledge of only a single kinematic parameter (a_2).
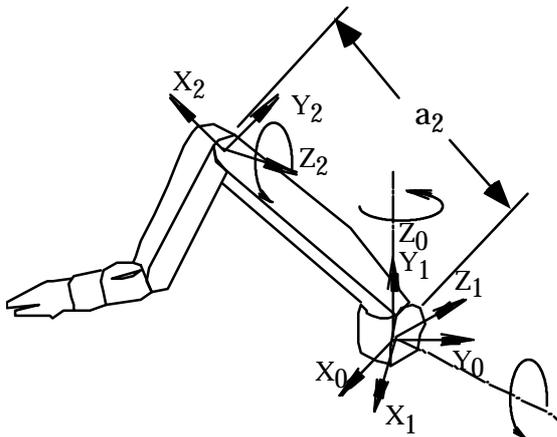

Fig. 4. Schilling Titan II coordinate frames

4. APPLICATION TO SCHILLING TITAN II HYDRAULIC MANIPULATOR

The Schilling Titan II is a six d.o.f. industrial hydraulic manipulator, shown in Figure 1. The Titan II is a widely used hydraulic manipulator in undersea and nuclear applications. It is attractive because of its high strength, low weight, and large workspace. However, the manipulator suffers from poor dynamic characteristics, largely due to high joint friction. Performance during small, slow motions is dominated by nonlinear friction effects. Further, it is very difficult to model the actuator and joint characteristics (Habibi and Richards, 1994; Electricité de France, 1996; Merritt, 1967).

In this study the control system is implemented with a Sun 3/80 interfaced to a VME bus. The control software is run on a 68030 single-board computer. Position feedback from the Titan II's joints is measured with resolvers, and dedicated hardware converts the resolver signal to quadrature waves with an effective resolution of 0.087 degrees. For all experiments, the sampling rate was seven milliseconds, which was sufficiently fast for fine motion experiments. For a more detailed description of the experimental system, refer to (Iagnemma, 1997).

5 EXPERIMENTAL RESULTS

5.1 Free Motion

The first task presented is for the third joint of the Titan II to track a 1.5 degree magnitude triangular wave at 0.1 Hertz. Due to the Titan II's very high levels of joint friction, this desired motion is difficult to execute. The commanded trajectory magnitude corresponds to approximately 17 counts of the quadrature-converted resolver signal.

The benchmark against which control performance is compared is PI control. Proportional and integral gains were tuned to be at 75% of the level causing structural oscillation. Figure 4 compares the performance of traditional proportional-integral (PI) control (dashed line) and proportional control with base-sensor feedback (solid line). For motions of this magnitude, PI control requires a relatively long time (6 seconds) to reach zero-error tracking. Base-sensor feedback allows the manipulator to achieve good tracking performance within a much shorter (0.5 second) time. Due to the integral nature of both controllers, tracking performance lags at velocity sign changes (when the frictional force changes direction).
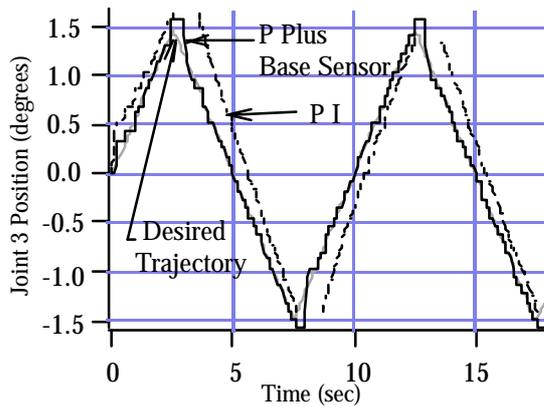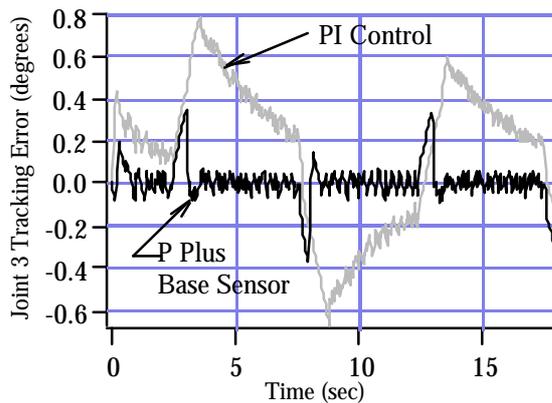
Fig. 4a. Tracking Comparison

Fig. 5a. Tracking Comparison

Fig. 4b. Error Comparison

Fig. 5b. Error Comparison

Figure 4b shows the joint angular errors of the two control approaches, and Table 1 qualitatively compares the results. Proportional control with torque estimation achieves a 77% improvement in RMS error over PI control, and the maximum error is substantially reduced.

Table 2 compares the error of the two types of control for this trajectory. Base sensor feedback achieves a 54% improvement in RMS error over PI control. While some errors remain, recall that this is a very large, powerful manipulator with very high joint friction performing a very slow and small motion, a very difficult task for it.

Table 1. Results for 1.5° triangular wave tracking

Controller Type	RMS Error (deg)	Maximum Error (deg)
PI	0.3671	0.7860
P + Base Sensor Feedback	0.0861	0.3460

Table 2. Results for 0.5° triangular wave tracking

Controller Type	RMS Error (deg)	Maximum Error (deg)
PI	0.1863	0.4480
P + Base Sensor Feedback	0.0845	0.2520

Figure 5a compares performance of the same controllers with the same gains executing 0.5 degree, 0.1 Hertz triangular waves, which correspond to a magnitude of approximately 6 counts, and velocity of 2 counts per second.

At these very low speeds, proportional control with base-sensor feedback requires slightly longer to compensate for friction at velocity sign changes (1 sec). However, zero steady-state error is still achieved.
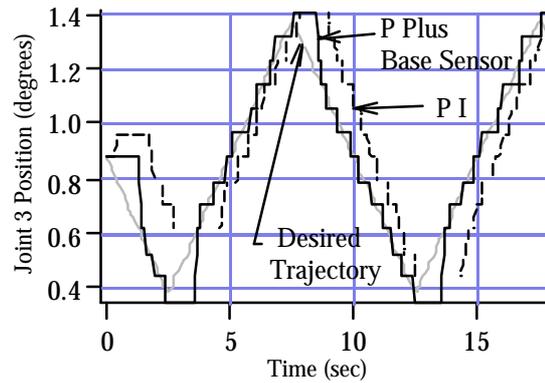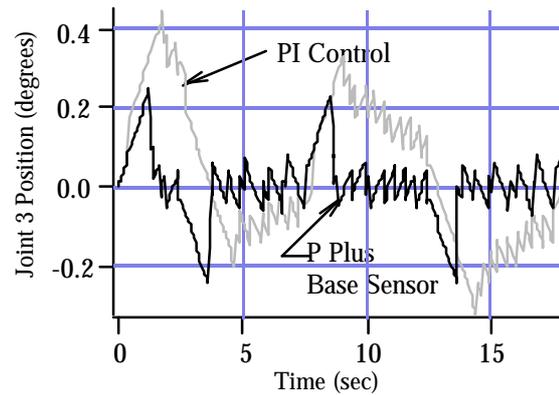
5.2 Cartesian-Space Free Motion

Cartesian-space tasks are more typical of practical applications. Here, a cartesian task was designed using joints two and three of the Titan II manipulator. The desired endpoint trajectory was a small circle of 15 mm radius at a speed of .166 rpm. Recall that the manipulator has a reach of approximately 1.9 meters. Joint-space paths were computed off-line using inverse kinematics. Errors were formed in joint space, and thus the control scheme is unchanged.

What is unique to this experiment is that coupled motion between joints with two parallel axes is required. The axes of rotation of joints two and three are parallel. The simplification of the torque estimation equation (i.e. the removal of dynamic terms for the torque estimation of joint 3) is thus explicitly tested.
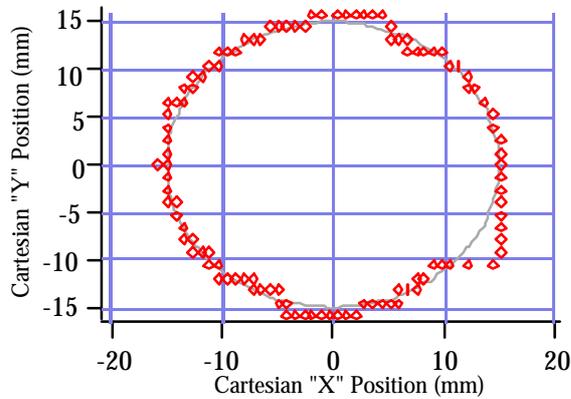

Fig. 6a. Cartesian Space Tracking--Base-Sensor
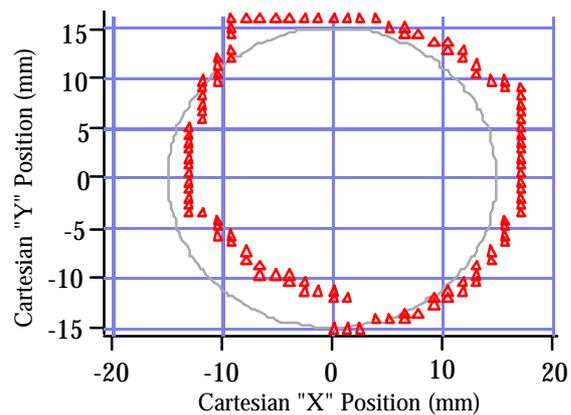   Feedback Control

Fig. 6b. Cartesian Space Tracking--PI Control

The effectiveness of the model-free base-sensor controller is shown in Figures 6a and 6b. Table 3 gives a numerical summary of the results. Clearly, the method makes a significant improvement.

Table 3. Results for cartesian-space tracking

Controller Type	RMS Error (mm)	Maximum Error (mm)
PI	3.033	4.643
P + Base Sensor Feedback	0.776	1.365

5.3 Free Motion With Payload

Many industrial tasks require accurate positioning of heavy payloads, such as the placement of the steam generator nozzle dam during nuclear power facility maintenance (Habibi and Richards, 1994). A control system must therefore be robust to variations in the

effective inertia of the system, and should provide high-performance control in both loaded and unloaded states. The Titan II is a very lightweight arm (77 kg). However, an ungeared, lightweight arm which is capable of supporting large loads will be subject to dramatic variations in the effective manipulator inertia tensor, a difficult control problem. While adaptive control methods can be applied, they have limitations (Craig, 1988). Here it is shown that the model-free control scheme is robust enough to deal with these variations, and still provide accurate tracking performance.

The commanded task was for the third joint of the Titan II to perform one degree sine wave tracking at 0.1 hertz while supporting a payload. The payload has a weight of 210 Newtons, a load that is approximately 30% of the Titan II weight. However, since the maximum torque capacity of joint 3 is 1200 Nm, a fully extended payload represents only 17% of the Titan II's maximum lift capacity.

Figure 7 compares the tracking performance of PI control and P control with base sensor feedback. From these results it can be seen that even with a small payload, the performance of PI control is substantially degraded. For the base sensor feedback case, rapid response to friction sign changes and to initial control switching (at time=0) is exhibited, zero-error tracking is achieved.

The rapid tracking of the system with base sensor feedback implies that the system bandwidth has been increased. This result follows the conclusions drawn for electrical systems (Pfeffer, *et al.*, 1989; Vischer and Khatib, 1995).
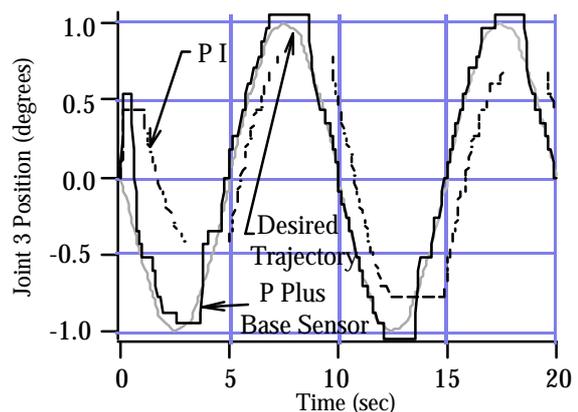

Fig. 7. Tracking Comparison with payload

6. SUMMARY AND CONCLUSIONS

In this paper, a simplified, model-free form of base-sensor control method has been applied to a hydraulic manipulator (Morel and Dubowsky, 1996). The simplified method is shown to be effective for very small, low-speed motions. Such motions are

difficult for most manipulators. Base-sensor feedback allows accurate control of joint torques, which leads to improved tracking performance during fine motions, where friction dominates. Compensation for coulomb friction at velocity sign changes is accomplished much more rapidly than with conventional methods. Base-sensor feedback also acts to minimize the effect of the payload on the external position loop, thus allowing accurate tracking and positioning that is robust to payload mass and inertia. The controller is easy to implement and is computationally very simple.

7. ACKNOWLEDGMENTS

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