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HIGH PERFORMANCE CONTROL OF MANIPULATORS USING BASE FORCE/TORQUE SENSING

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Abstract

Joint friction is a major problem in accurately controlling manipulators performing small precise tasks. Previously developed solutions to this problem require the use of either complex and unreliable models of the joint friction or expensive and delicate internal joint torque sensors. Here a simple, cost-effective method for compensating the effect of joint friction is proposed. It uses a six-axis force/torque sensor mounted externally at the manipulator's base. From the base wrench measurements, the joint torques are estimated and fed back through a torque controller, that virtually eliminates friction and gravity effects. It is shown that with this high-quality torque control a simple PD position controller can provide very high precision motion control. The precision is substantially greater than for conventional methods and approaches the resolution of the Puma's encoders.

1. Introduction

Robotic manipulators are often required to perform very small, very accurate, and very slow motions, such as for micro-assembly. Precision is difficult to achieve due to the effects of nonlinear joint friction. To solve this problem three approaches been developed: model based compensation; torque pulse generation; and torque feedback control. In the first, an accurate model is needed to estimate of the friction torque [1,2,3]. The method has important limitations. It is very difficult in practice to obtain accurate and robust models that can faithfully account for many nonlinear phenomena such as Coulomb friction, dependency on joint position, influence of changes in load and temperature and nonbackdriveability.

In the torque pulse method, pulses to compensate for friction are generated using either an explicit model [1] or simple rules of qualitative reasoning [4]. While this is a practical approach the method is limited to cases where the trajectory to reach the final position is not important, since only finite displacements are controlled.

In torque feedback control the torque applied to a manipulator’s joint is sensed and fed back in a joint torque loop. This method has produced good and robust experimental results; reducing the effective friction torque by up to 97% without the need for any friction model [5,6]. Unfortunately, most commercially manipulators are not equipped with joint torque sensors. Installing them in an existing manipulator would be very difficult [7]. Also, such sensors introduce number of practical problems. For example, they can add structural flexibility, that can decrease the overall performances of the manipulator, they are expensive, and they can reduce system reliability.

Here, a new approach is presented to deal with joint friction during fine motions, that overcomes the difficulties of the three discussed above. The method uses a six-axis force/torque sensor mounted between the manipulator and its base to estimate joint torques. The estimation process uses Newton-Euler equations of successive bodies. The estimated torques are used in joint torque loops. An outer position control loop provides the desired torques from measured position errors, see Figure 1.

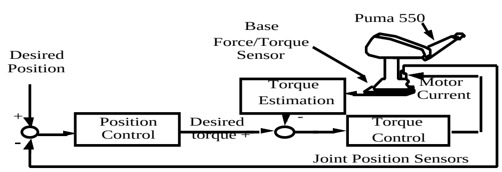


Figure 1. High precision control structure using a base force/torque sensor

2. Joint torque measurement using base sensing

Consider a manipulator mounted on a base force/torque sensor. The wrench W_b exerted by the manipulator on its supporting sensor is:

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

W_g is the wrench due to the gravity and W_d is the dynamic wrench due to the motions of the manipulator. Note, the base sensor measures wrenches only due to forces and torques effectively to the manipulator's links. Transmission and joint friction do not appear in the measured base wrench.

The first step in the process is to estimate the dynamic component, W_d, by compensating for the gravity component W_g as follows [8]:

$$W_d = W_b - W_g = W_b - \begin{pmatrix} F_g = \sum_{i=1}^{n} m_i g \\ M_g^{O_s} = \sum_{i=1}^{n} O_s G_i \times m_i g \end{pmatrix} \quad (2)$$

Where F_g and $M_g^{O_s}$ 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 center of mass of link i, respectively. The gravity compensated wrench (W_d) is then propagated through the successive bodies of the manipulator to yield an estimate of the dynamic joint torques, as follows:

$$\begin{cases} W_{0\to1} = -W_d \\ W_{1\to2} = W_{0\to1} - W_{dyn_1} \\ \quad\vdots \\ \quad\vdots \\ W_{i\to i+1} = W_{i-1\to i} - W_{dyn_i} \end{cases} \quad (3)$$

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

$$W_{dyn_i} = \begin{pmatrix} F_{dyn_i} = m_i \dot{V}_{G_i} \\ M_{dyn_i}^{A} = I_i \dot{\omega}_i + \omega_i \times I_i \omega_i + G_i A \times m_i \dot{V}_{G_i} \end{pmatrix} \quad (4)$$

I_i is the inertia tensor of link i at G_i. Summing the equations (3) yields:

$$W_{i\to i+1} = -W_d - \sum_{j=1}^{i} W_{dyn_j} \quad (5)$$

Given this wrench, the torque in joint i+1 is obtained by projecting the moment vector, $W_{i\to i+1}$ acting on the ith+1 link along the z_i axis of the ith link:

$$\tau_{i+1} = -z_i^t \left[M_d^{O_i} + \sum_{j=1}^{i} \left(I_j \dot{\omega}_j + \omega_j \times I_j \omega_j + O_i G_j \times m_j \dot{V}_{G_j} \right) \right] \quad (6)$$

2. Design of a torque controller for a Puma 550 using base sensing.

Experimental studies with the Puma show that its joints exhibit very large Coulomb friction [9]. In very fine motion applications this friction will severely degrade systems performance. Here a torque controller using base force/torque sensing is used to compensate for this static friction. The torque estimation requires measurement of joint positions, velocities and accelerations. For the Puma the positions are measured with incremental encoders. This encoder data is differentiated and filtering, at a sampling rate of 2500Hz, yields the velocities and accelerations. The required mass parameters of the links are estimated from the base force/torque sensor static data [10]. The method for joint torque estimation applied to the Puma 550 is not computationally intensive. A single 68020 VME board, supporting VxWorks, can estimate the joint torques, including gravity compensation, at sampling rate of 300Hz.

The torque control law discussed here is a form of high DC gain controller implemented as an integral controller [11], but with feedforward compensation, or:

$$V_{command} = \frac{1}{K_{act}} \left[\tau_{des} + K_{int} \int_0^t (\tau_{des} - \tau_{est}) \right] \tag{7}$$

τ_{des} and τ_{est} are the desired and the actual (i.e. base-sensed) torques, respectively and K_{act} is a constant based on the amplifier, motor and transmission parameters. The gain K_{int} was set to 75% of the value that caused experimental structural oscillations.

Figure 2 demonstrates the effectiveness of base sensed torque control for the first joint of the Puma 550. Here, the desired torque is a triangular function with a maximum value of 3 Nm, while the dry friction is more than 5 Nm. Without torque feedback, the actual torque applied to the link would simply be zero, as the friction would be larger than the motor torque. However, with torque feedback, the experimental results show that the actual torque remains very closed to its desired value (Figure 2). The torque controlled motor must produce nearly 8 Nm to obtain the next 3 Nm required by the command. Results obtained in the study show that when the sign of the velocity changes (such as at approximately 3.2s, 5.35s and 6.5s in Figure 2) large torque disturbances occur. Even at these times the torque error peak remains small (±1 Nm, i.e., 20% only of the Coulomb friction) and is quickly brought under control [9].

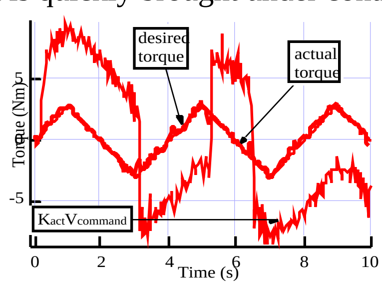


Figure 2: Joint 1 torque control experimental results

3. Position control with base sensed torque feedback control

Experiments showed that with the based sensed joint torque feedback method the manipulator could be made to appear virtually frictionless. With such quality performance, it is easy to obtain precise position control using a simple PD loop enclosing the torque controller. Consider the simple controller (see Figure 3):

$$V_{command} = \frac{1}{K_{act}} \left[\tau_{des} + K_{int} \int_0^t (\tau_{des} - \tau_{est}) \right] \quad (8)$$

with

$$\tau_{des} = K_p (q_d - q) + K_d (\dot{q}_d - \dot{q}) \quad (9)$$

Where K_p and K_d are the proportional and derivative diagonal gain matrices, respectively.

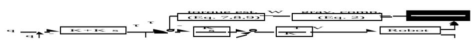
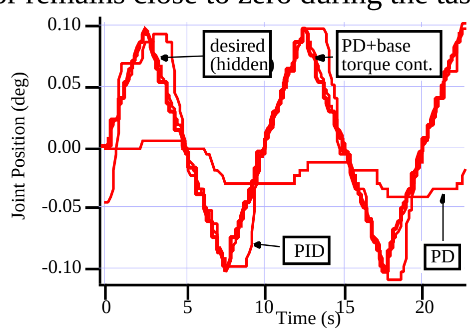


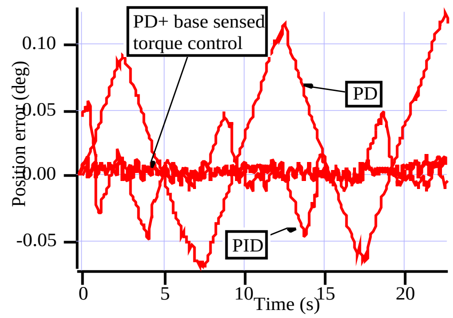
Figure 3. The precise position control scheme with base sensed torque feedback

The robustness and effectiveness of the method at the joint level is show in Figure 4. Here joint 1 is commanded to follow a very slowly a triangular wave. The magnitude of the desired motion is +/-0.1 degrees, with a period of 10 seconds. This corresponds to a desired velocity of 7 encoder counts per second.

In Figure 4 shows the performance of the Puma with base sensed torque control compared to conventional PD and PID controllers. For all three controllers, the gains have been chosen to provide a bandwidth of 5 Hz and a damping ratio of 0.5. The integral gain in the PID control has been selected to be quite high, equal to 80% of the smallest value exhibiting instability. In Figure 4 the superior performance of the base sensed torque control is clear. Conventional PD control leads to almost no motion, due to dry friction. The PID controller performs much better, and provides a zero steady state positioning error. However, when the sign of the velocity changes, the position integral compensator requires a long time (2.5 s) to compensate for the friction disturbance, resulting in lack of positioning precision. The base sensed torque feedback control method compensates rapidly for the Coulomb friction at velocity sign changes (~50 ms) and the position error remains close to zero during the task.



a: Tracking performance



b: Position error

Figure 4. Precise position control results for Joint 1.

Table 1 summarizes the performances of the three controllers. The base sensed torque control results show error on the order of magnitude the resolution of the encoder are reached. An encoder count corresponds to a 0.0058 degree angle, and thus the Root Mean Square error (0.0042 deg) is less than one encoder count throughout the entire task.

Table I. Summary of position control performances.

Controller	Max. Error (deg)	RMS error (deg)	Integral Sq. error ($deg^2 s$)
PD	0.12	0.0590	$7.7\ 10^{-2}$
PID	0.056	0.0200	$9.1\ 10^{-3}$
PD with base sensed torque control	0.012	0.0042	$4.0\ 10^{-4}$

Figure 5 shows the ability of the manipulator with based sensed torque control to precisely tract a delicate Cartesian space trajectory. The desired end-effector trajectory is a circle with a 350μm radius. The maximum magnitude of the joint motions is 0.1 degrees. For these very fine motions the algorithm can be substantially simplified without loss of performance. First, W_g is assumed to be constant. It is simply set equal to the initial static wrench measured with the base sensor. Second, all the dynamic terms are neglected.

In the results show in Figure 5 the end-effector position is measured by a fixed 2D photodetector sensor and a laser mounted on the end-effector. The precision of the system is clearly excellent: the maximum absolute position error is less than 30μm, in spite of large frictional disturbances that occur each cycle of the motion when the sign of the velocity for each of the joint changes.

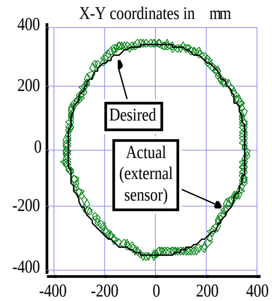


Figure 5. Cartesian tracking results

4. Summary and conclusions

A new and practical method to compensate for joint friction in fine motion control of manipulators has been proposed. It does not require either the difficult modeling of friction or the use of expensive and delicate internal joint torque sensors. It uses a 6 axis force/torque sensor mounted at the base of the manipulator. The sensor is external to the robot and hence can be easily mounted under existing manipulators.

The experimental results show dramatically fine performance. At the end-effector, during very slow displacements, the position error remains smaller than 30μm. This method is now being investigated for delicate tasks that require both fine motions and very small interaction forces.

5. Acknowledgments

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6. References

1. B Armstrong, Control Of Machines With Friction, Kluwer Academic Publishers, Boston, USA, 1991

2. M.R Popovic, K.B. Shimoga and A.A. Goldenberg, Model Based Compensation Of Friction In Direct Drive Robotic Arms, J. of Studies in Informatics and Control, Vol. 3, No 1., pp. 75-88, March 1994.

3. C. Canudas de Wit, Adaptive Control Of Partially Known Systems, Elsevier, Boston, USA, 1988.

4. M.R. Popovic, D.M. Gorinevsky and A.A. Goldenberg, Accurate Positioning Of Devices With Nonlinear Friction Using Fuzzy Logic Pulse Controller, Proc. Int. Symposium of Experimental Robotics, ISER' 95, pp. 206-211.

5. J.Y.S. Luh, W.B. Fisher and R.P. Paul, Joint Torque Control By Direct Feedback For Industrial Robots, IEEE Trans. on Automatic Control, vol. 28, No 1, Feb. 1983.

6. L.E. Pfeffer, O. Khatib and J. Hake, Joint Torque Sensory Feedback Of A PUMA Manipulator, IEEE Trans. on Robotics and Automation, vol. 5, No 4, pp. 418-425, 1989

7. Hake J.C. and Farah J., Design Of A Joint Torque Sensor For The Unimation PUMA 500 Arm, Final Report, ME210, University of Stanford, CA, 1984

8. H. West, E. Papadopoulos, S. Dubowsky and H. Chean, A Method For Estimating The Mass Properties Of A Manipulator By Measuring The Reaction Moment At Its Base, Proc. IEEE Int. Conf. on Robotics and Automation, pp , 1989

9. Morel , G. and Dubowsky, S., The Precise Control Of Manipulators With Joint Friction: A Base Force/Torque Sensor Method, Proc. IEEE Int. Conf. on Robotics and Automation, pp , 1989, Minneapolis, MN, April 24-27, 1996.

10. T. Corrigan and S. Dubowsky, Emulating Micro-Gravity In Laboratory Studies Of Space Robots, Proc. ASME Mechanisms Conf., pp. , 1994

11. R. Volpe and P. Khosla, An Analysis Of Manipulator Force Control Strategies Applied To An Experimentally Derived Model, Proc. IEEE/ RSJ Int. Conf. on Intelligent Robots and Systems, pp. 1989-1997, 1992