

Force Override Rate Control For Robotic Manipulators

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1 Abstract

The work reported deals with the problem of operating a robot manipulator under a rate control mode while the end effector is not in contact with the external environment, and then switching to a force control mode when contact is made. The paper details how the modal changeover may be accomplished in a manner transparent to the operator, and will allow operator applied forces to be reflected at the robot end effector. A one degree of freedom demonstration system is used to illustrate the concept, which is then applied to a PUMA manipulator. Sample code for the implementation of the control is provided, experimental results show that the optimum setting for the gain is a function of the compliance of the end effector, and the compliance of the external constraint.

2 Introduction

Many conventional robot manipulators operate either in rate, or in positional control modes. That is to say that a command issued by the operator causes the end effector of the manipulator to move with a particular velocity in a certain direction, or to move in a specified direction a given distance. Intuitively, this is the most useful form of motion required of a manipulator, since it can be used to accomplish a wide variety of tasks involving the positioning of objects for assembly tasks, or the performance of speed related tasks such as welding, or grinding.

Another class of motions for which manipulators may be used may be classified as force control problems. In these cases, it is required to develop forces and perhaps moments between the manipulator and an external environment, in order to perform the required task. Examples of application of force control would include removing a module from a satellite in the cargo bay, or assembling components of the space station structure. Clearly, more than simple motion of the end effector is required, and some knowledge, and subsequent control of the interactive forces and moments developed between the manipulator and the environment in which it works, has to be established.

3 Background

Force control of robotic manipulators is an established subject with an extensive literature [1], [2], [3], [4], [5], [6]. Much of the existing work is focussed on how to transform force and moment requirements expressed in the world or task frame, to torques exerted by the individual joints of the manipulator. An example of this might be where a manipulator is attempting to insert a screw. The problem to solve is: what robot joint torques provide a torque about the screw axis, and a downward force on the screwdriver to accomplish insertion. This problem, and many like it, are solved by using the manipulator Jacobian to relate forces and moments expressed in terms of joint and world coordinate frames. Since the Jacobian relates differential displacements in these two frames, we may write

$$\delta\mathbf{x} = \mathbf{J}\delta\mathbf{q} \quad (1)$$

where the differential displacement in the world frame is $\delta\mathbf{x}$, while the differential displacement in the tool frame is $\delta\mathbf{q}$. The principle of virtual work may be used to derive

$$\boldsymbol{\tau} = \mathbf{J}^T\mathbf{F} \quad (2)$$

where $\boldsymbol{\tau}$ is the vector of joint torques and \mathbf{F} is the vector of forces and moments expressed with respect to the world frame. Although most manipulators implement equation 1 to relate world and joint motions, few if any implement equation 2, enabling engineers to control world space forces by controlling individual joint torques. Even if this were available, the task of accurately controlling joint torques¹ is very difficult.

In the majority of tasks in which we are interested, man in the loop, rather than computer control, is the normal mode of operation. In such operations, the forces needed to accomplish a particular task are not specified analytically, rather, they are generated by the operator in a natural manner. Inserting a screw is a good example of this. All that is required is to feed back to the operator a measure of the forces generated by the manipulator as it performs the task, enabling a reduction or increase in force as appropriate. This scenario is usually described as bi-lateral teleoperation.

In the work described here, we use a simple adaptation of conventional position and speed controlled manipulation tasks to achieve force control in a natural and operator transparent manner. In addition, the system is not strictly bi-lateral in nature, although the operator does experience the forces being applied to the remote manipulator. The overall system provides a simple means to implement force control strategies on existing manipulation systems in order to accomplish assembly-type tasks.

4 Single Degree of Freedom Force Control System

The system is meant to simulate a one degree of freedom actuation system operating in rate and force mode, i.e. on a commanded signal, the output of the system achieves a velocity proportional to the input. The system schematic is shown in figure 1.

¹usually by controlling motor current

A simple center-off toggle switch represents the rate input signal, and may be either zero, positive or negative. The switch output drives an electro-hydraulic servo valve which is connected to a hydraulic cylinder. Using this arrangement, the piston rod may be driven in either direction at a constant speed, or held stationary when the switch is in the center position. The end-effector attached to the cylinder rod now has to interact with an external, compliant constraint, and has to exert operator applied forces to it.

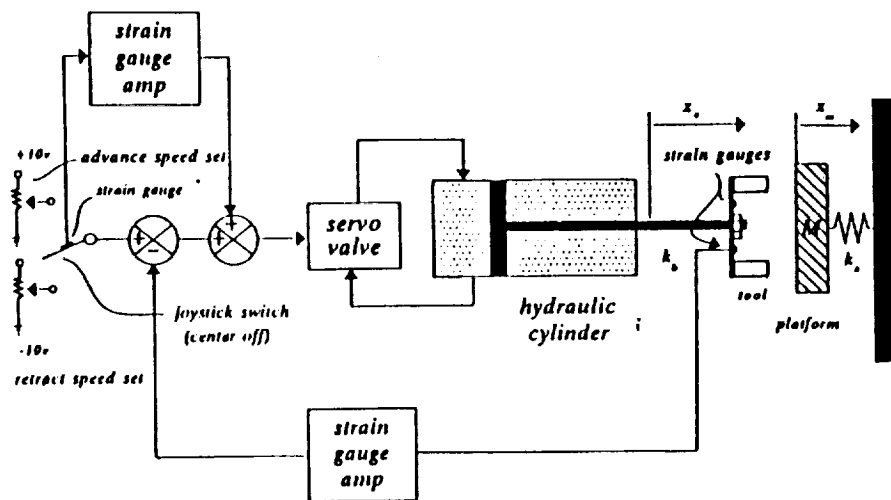


Figure 1: Force Override Control System

A strain gauge is attached to the extended handle of the toggle switch, and another strain gauge fixed to the stiff, but compliant part of the end effector, as shown in figure 2.

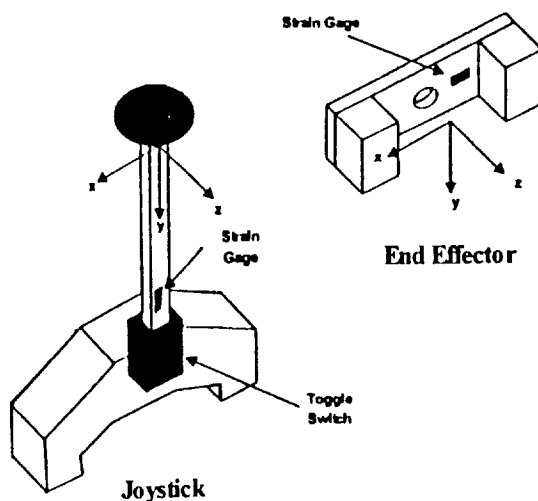


Figure 2: Strain Gauge Placement on Joystick and End Effector

The strain gauge on the end effector now acts as a mechanism to prevent large forces being

applied to the spring loaded plate, representing the external environment, by feeding back its signal to a summing junction following the toggle switch. By moving the toggle switch off the center position, the ram will advance at a constant speed until contact with the plate occurs. Further motion of the ram increases the feedback signal, reducing the ram speed until equilibrium is achieved with the ram stationary, and a finite deflection of the plate. This deflection may be adjusted by the feedback strain gauge amplifier gain,

At this point, the operator may press forward on the toggle switch handle, generating a signal from the strain gauge attached to it. This signal is added to the forward path signal causing further advancement of the ram. Pulling back on the lever will reduce the contact force. Returning the toggle switch to the off position will cause the ram to retract until the end effector is just touching the plate, theoretically with no interactive force between them.

In this manner, the forces applied by the operator to the control handle are reflected to the end effector. Although no force signal is fed back to the operator, because he/she is applying the demanded force to a compliant member, some knowledge of the magnitude of the applied force is sensed. The ratio of demanded and actually exerted forces may be scaled up or down using the forward path gain.

If the dynamics of the servo valve are considered to be faster than the rest of the system, the block diagram of the force override rate control system appears as shown in figure 3.

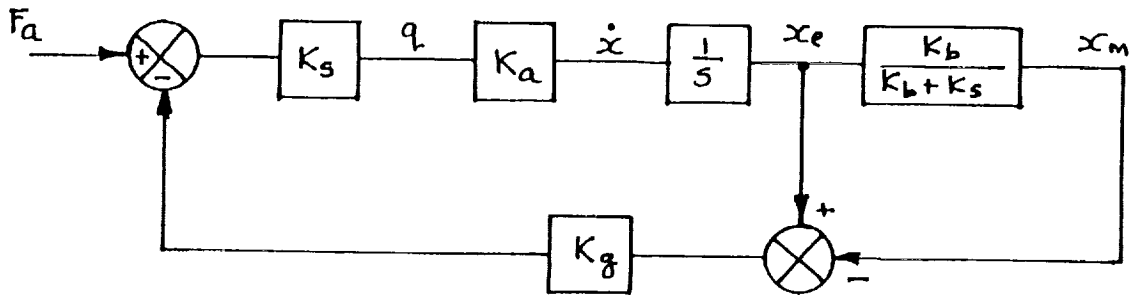


Figure 3: System Block Diagram

In the figure, we define: K_g = strain gauge amplifier gain, K_s = servo valve constant, K_a = actuator gain, K_b = end effector stiffness, and K_s = constraint stiffness. Since the open loop transfer function may be written as

$$GH(s) = \frac{K_s K_a K_g A}{s} \quad (3)$$

where

$$A = 1 - \frac{K_b}{K_b + K_s} \quad (4)$$

and is clearly a positive constant, it appears that the system is first order. The step response may be expected to be exponential, with a time constant selectable by the forward path gain. Experimental results, though not presented here, confirmed the result.

4.1 Robot Manipulator Based System - One Degree of Freedom

In this phase of the work, the preceding concept was applied to an industrial manipulator, a PUMA 560, in order to determine the functional requirements of a commercial controller which could accommodate the force control system. Figure 4 shows a schematic of the system, and indicates how the toggle switch controller and end effector from the electro-hydraulic test facility were simple changed to the robot facility.

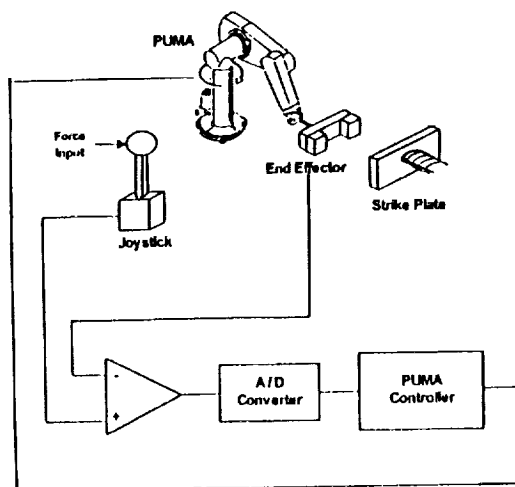


Figure 4: Force Override Using Manipulator

The force error is determined by analog equipment, so the problem is to firstly communicate the magnitude of this error to the PUMA controller, and then to drive the manipulator in an appropriate manner in response to the error. The first problem was solved by simple A-D conversion, at about 200 Hz, and connecting the resultant eight bit number to the PUMA controller parallel port.

Moving the manipulator in response to the resultant force error is somewhat machine specific, but results for the PUMA are presented in detail since most manipulators offer a similar programming environment, and so the algorithms should be easily transportable to other platforms. The resultant code is as follows, written in the VAL II language.

```

20  prompt 'Calibrate (1) or run (2)';c
    if c=2 goto 10
    rate=25
    signal 1,2,3,4,-5,-6,-7,-8
    cv=bits(1001,8)
    type 'Calibrated value=';cv
    goto 20

```

```

10  x=bits(1001,8)
    z=(cv-x)/rate
    if(abs(z))<2 goto 10
    type x,z
    departs z
    goto 10

```

The first half of the program, between lines 20 and 10, reads the A-D converter to obtain a current value. This allows for drift in the analog part of the system. At line 10, the A-D converter is read into x , and a target displacement z calculated. This value actually corresponds to a speed, since the program executes the loop recursively, hence the motion of the tool is observed as a constant speed. The actual speed may be varied to a convenient value by the experimentally determined variable $rate$. The motion command $departs z$ causes the end effector to move in a straight line z centimeters in the direction of the positive z axis. Because the loop is executed about every 50 msecs, new force errors from the A-D converter are read in each time. In addition, a dead space of 2 reduces spurious motion of the end effector due to noise and vibration causing the A-D converter output to vary in a random manner. This program exhibits both rate control of the PUMA, and force control when driven by the joystick.

The selection of the variable $rate$ will affect the operation of the system. If the manipulator is in contact with a very stiff spring, and the force error commands the tool to advance, say 10 mm, large forces will be developed before the control loop next examines the force error, and retracts the tool. The effect of changing $rate$ is the same as changing the forward path gain in an inverse sense, i.e. increasing $rate$ decreases the forward path gain. In this experiment, and the one described next, the forward path gain has to be determined by considering the external stiffness with which the manipulator interacts, so as to prevent the development of large forces.

4.2 Robot Manipulator Based System - Multi-Degrees of Freedom

To implement this phase of the work, it was decided to try to make the end effector of the PUMA apply three dimensional forces exerted by the operator on a compliant joystick. Figure 5 shows the design of both the joystick and end effector attached to the PUMA.

In this design the forces applied in the x , y and z directions of the joystick frame are decoupled by means of the placement of strain gauges. Gauges are placed in identical locations on the end effector. In designing these units, the stiffness in each of the three directions was made the same. Commercial force/torque sensor units could be used instead.

Force errors in each of the three directions were generated in analog mode with the use of three differencing junctions. These force errors were then fed to a multi-input A-D converter which the PUMA could address. The software for acquiring the analog signals and moving the PUMA in response to them is very similar to that written for the one degree of freedom discussed earlier.

Test were performed on the system by observing the step response of the force applied by the robot tool to a demanded force applied at the joystick. The applied force was generated by applying a static load in the required direction on the joystick. Force outputs in the x , y and z directions at the tool were recorded, for various settings of the servo-system forward path gain β . Experimental

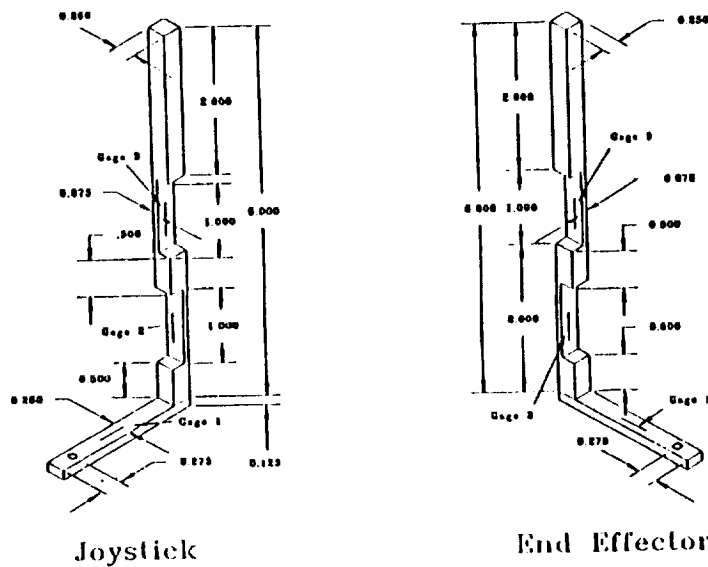


Figure 5: Force Sensing Joystick and End Effector

data, for increasing β , are shown in figures 6, and 7. In these tests, the tool interacted with the same spring loaded plate constraint described earlier.

5 Discussion of Results and Conclusions

Although developed in a heuristic manner, the concept of a force control system overriding a rate control system appears to perform as expected. Operator applied forces and moments may be reflected at the end effector, with the operator experiencing some measure of the forces being applied. In the purely analog implementation using a one degree of freedom electrohydraulic actuator, the response time may be freely adjusted by means of the forward path control system gain.

In applications in which sampling of the force, or force error is used to drive the actuator, the response is a function of the forward path gain, the compliance of the end effector and the compliance of the constraint against which the end effector reacts. The external stiffness has to be known before the limiting gain, consistent with stability, may be determined. Examples of such unstable response corresponding to increased gain may be seen in figures 6 and 7.

Since prior knowledge of the environmental compliance is needed to set the system gain to obtain acceptable response, a system with fixed gains cannot provide optimum response for all tasks it has to perform. If the external stiffness is unknown, the manipulator needs to carefully probe the environment in order to determine the nature of the constraint it is dealing with. Once this has been determined, the system gains may be adaptively set to deal with the task. It will be expected that different responses will be obtained from objects constrained by springs (of varying stiffnesses), and objects subject to purely inertial forces, such as a freely floating satellite. Current work is being directed to this area.

The implementation of the force override system has been implemented on a particular robotic platform, but the concept is general enough to be transferred to most manipulation systems. One advantage of the system is its ability to be overlaid onto an existing manipulator and controller

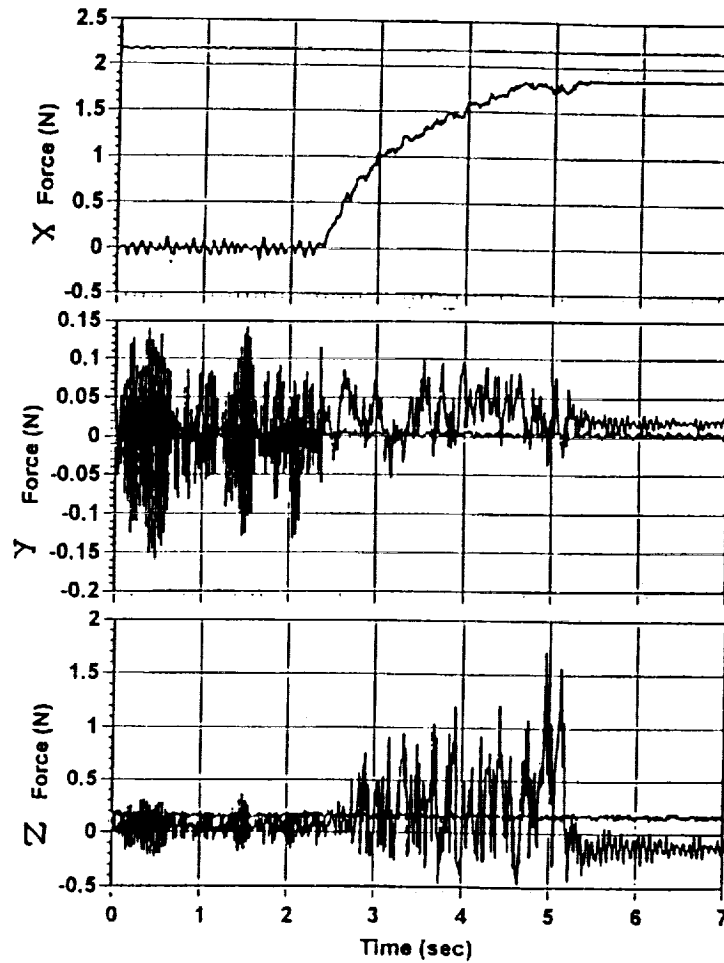


Figure 6: Step Response in x Direction for $\beta = 0.5$

combination.

6 Acknowledgement

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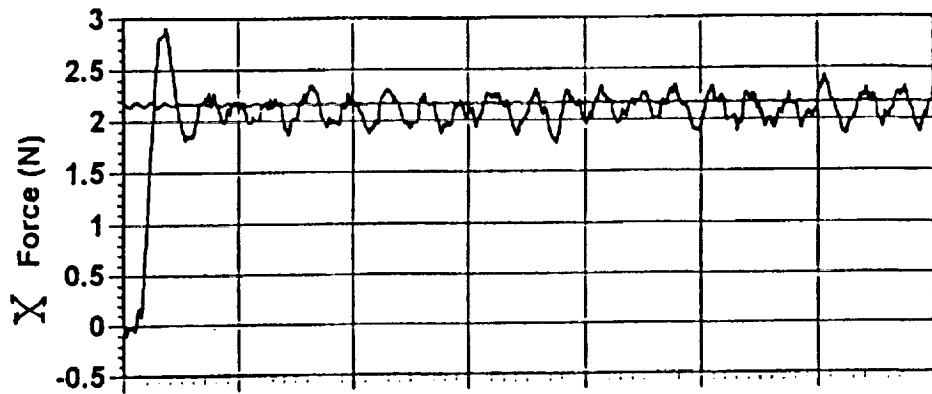


Figure 7: Step Response in x Direction for $\beta = 4.0$

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NASA Shuttle Logistics Depot Support to Space Station Logistics

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Over the past 25 years, Space Logistics has undergone a great evolution in thought and practice. We have progressed from a "Fire and Forget" posture to providing complete integrated logistics support for a reusable spacecraft with a multimission role. This shift in the framework of Logistics has influenced the various design communities in their endeavor to support the changing requirements for the types of hardware necessary to meet the space flight mission challenges.

We are about to embark on the next evolutionary step from the reusable spacecraft to a permanent on-orbit facility. This facility will have the capability of supporting human life over a 30-year period. Many new challenges to our Logistics systems must be met with the same emphasis on innovation as has led us in the past. We must be careful to take full advantage of the lessons learned on the Shuttle Program, as well as to develop new approaches and techniques to solve the many challenges that confront us with the Space Station Program.

Session S2: SPACE MAINTENANCE AND SERVICING

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