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Dynamic Simulation of Virtual Mechanisms with Haptic Feedback Using Industrial Robotics Equipment

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Abstract

This paper explores using industrial robotics equipment in a haptic (or kinesthetic) force display system conceived for mechanism design applications. The dynamics and kinematics of an aircraft flight control column/wheel are simulated as a human interacts directly with the end effector of a commonly available robotic manipulator. An admittance control paradigm is used for developing a haptic system wherein realistic simulation of the dynamic interaction forces between a human user and the simulated virtual object or mechanism is required. Experimental results are presented which demonstrate human user interaction with the virtual mechanism.

1 Introduction

Although the idea of incorporating force feedback in mechanical systems has been around for quite some time [1], design and analysis of haptic (or kinesthetic) feedback mechanisms is a relatively new field of study [2]. Much of the early work in this area was aimed at developing more robust and intuitive telemanipulation systems ([3],[4],[5], and [6]). In many of these systems, no attempt is made to precisely simulate the forces imparted to the human operator during interaction with the remote environment [5]. However, there is an increasingly broad range of applications (including astronaut training [7], molecular force simulation [2], and the kinematic analysis of mechanisms [8]) in which haptic feedback devices must provide high-fidelity interaction force simulation.

Thus far, most haptic system development has focussed on inventing new devices (an overview of several devices which have been developed can be found in [9]) with a fairly narrow range of intended applications that are known a priori. This has advantages because specific design criteria can be established and performance can be optimized. However, future applications may fall outside a particular haptic device's capabilities. Then, the device must either be re-designed or an entirely new device must be developed or purchased. Unfortunately, the costs associated with developing haptic devices are quite high (often over $100,000) limiting their use to a handful of research laboratories.

As an alternative, one might consider the use of off-the-shelf, general-purpose robotics equipment (often costing less than $30,000) in a haptic force display system [5],[6]. However, most general-purpose robots suffer from mechanical deficiencies that many claim make them unsuitable for use in a haptic display system.

A number of researchers (see [10], for example) have reported on the desirable characteristics of a haptic feedback device. The consensus seems to be that the "ideal" haptic interface device is one which has low friction, inertia and backlash, is highly backdriveable, has a large force range and high mechanical bandwidth, and has a suitable working volume. These can be conflicting goals. For example, larger working volumes and larger force capabilities require devices which are physically larger and which tend to have more inertia and friction coupled with a lower mechanical bandwidth. Therefore, an analysis of the intended application is required before selecting the appropriate device to use.

This analysis is required whether using off-the-shelf equipment or special purpose equipment. If the application requires simulation of a large range of interaction forces over a large range of motion, then the device's working volume may be a key consideration. However, force bandwidth may be the dominant decision criteria if the intended application requires the ability to "feel" high frequency vibrations. In many cases, there may be a commercially available device which meets the needs of a range of intended applications.

This paper addresses using a commercially available, general-purpose robotic manipulator to provide physics-based dynamic force interaction between humans and virtual objects or mechanisms. Accurate simulation of the kinematics and dynamics of mechanisms subject to human interaction alleviates the need to build expensive

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prototypes which in turn speeds up the design process.

We have found that a general-purpose, six-degree-of-freedom robot provides a great deal of flexibility in developing a wide range of haptics applications at a greatly reduced cost in terms of system development time and materials. Furthermore, other research facilities can easily obtain the necessary equipment while replicating and improving on the results of previous efforts.

2 The admittance control paradigm

The control systems of many haptic interface devices utilize open-loop force control [11]. Often, a simple open-loop controller is used which relates the interaction forces between the device and the user as

$$\tau = J^T F_{ext} \tag{1}$$

where τ is a vector of actuator forces and torques required to impart the interaction force and moment components in F_{ext}, and J is the Jacobian matrix.

Equation (1) assumes that disturbances such as inertia and friction remain negligible. Section 1 points out that this assumption would be true of the "ideal" haptic interface device. Many devices, especially commercially available equipment, can have substantial friction and inertia. A model-based controller can be employed which calculates the required actuator inputs to generate the desired interaction forces as

$$\tau = J^T F_{ext} + I(q)\ddot{q} + C(q,\dot{q})\dot{q} + V(q,\dot{q}) + G(q) \tag{2}$$

where I is the modelled inertial matrix of the haptic device, C is the modelled Coriolis and centripetal matrix, V is a vector of friction terms, G is the modelled gravity vector, and q represents the vector of the haptic device's generalized coordinates. Note that if the device has actuator dynamics which are important, additional modelling will be required.

Equations (1) and (2) are often used in open-loop controllers as the sole means to generate the haptic device's actuator inputs. However, typical system disturbances arising from measurement noise and imperfect modelling can lead to instability. Therefore, some type of feedback control is generally necessary to reject disturbances. Most haptic devices have controllers which are based on impedance theory [12] and its application to robotics. Impedance is thought of in terms of a physical system accepting a motion input and yielding a force output while its counterpart, admittance, implies a system which accepts force inputs and yields motion outputs. Typical haptic systems measure the position of the interaction port (the user/device contact point where energy is exchanged) and then derive control signals based primarily on a desired force output when the user interacts with a virtual object such as a stiff wall.

Another approach is to measure the interaction forces (and moments) at the interaction port and then derive control signals based on a desired motion output. This is referred to as an admittance control paradigm. Usually, when a robot is interacting with its environment it must act as an impedance while the environment acts as an admittance [12]. However, in a haptic system, there are two manipulators acting in series; a human manipulator and a mechanical manipulator. The admittance control paradigm assigns the impedance role to the human user and the admittance role to the mechanical haptic device.

This approach to haptic force display has been recently and independently applied using general-purpose robotics equipment in two different labs [9], [13], [14]. The phrase "admittance display mode" was coined in [14] to represent this approach to haptic force display.

The primary disadvantage with the admittance control paradigm as applied to haptic force simulation is that it requires direct measurement of the forces being applied at the interaction port. However, this would be necessary anyway if the intended application requires simulation of dynamic interaction forces in addition to static forces. Other advantages of incorporating force feedback are called out in [15]. In [15], a target impedance is specified as

$$\ddot{x} = M^{-1}\left(K(x_0 - x) - B\dot{x} - F_{ext}\right) \tag{3}$$

where M, B, and K correspond to the desired inertia, damping, and stiffness seen at the interaction port while x and its derivatives correspond to the desired interaction port trajectory. Equation (3) is then incorporated into a nonlinear Cartesian controller where K and B are essentially feedback gain vectors. The controller presented in [15] is referred to as a nonlinear impedance controller. In this approach, maximum stiffness and damping is limited by system stability requirements as K and B become large. Furthermore, if the specified target impedance represents a higher-order nonlinear system, stability and performance become more difficult to analyze and predict. For stability analysis, it is often desirable to decouple the feedback loop with trajectory generation so the control system feedback gains do not depend on the parameters of the simulated object or mechanism.

A closed-loop impedance controller might also have feedback gains to drive the errors between the desired interaction *force* and the actual interaction *force* to zero. A simple controller might take the following form:

$$\tau = J^T F_d + \Gamma_f(F_d - F_a) \tag{4}$$

where F_d is the desired interaction port force vector, F_a is the measured interaction port force vector, and Γ_f is a set of feedback gains.

A closed-loop admittance controller will have feedback gains to drive the errors between the desired interaction port *motion* and the actual interaction port *motion* to zero. In this case a simple controller will have the following form:

$$\tau = \Omega(x_d, \dot{x}_d, \ddot{x}_d) + \Gamma_p(x_d - x_a) + \Gamma_v(\dot{x}_d - \dot{x}_a) \tag{5}$$

where x_d represents the desired interaction port motion, x_a represents the measured interaction port motion, $\Gamma_{p/v}$ is a set of feedback gains, and Ω is a vector of model-based, feedforward actuator inputs.

Most general-purpose robots are position controlled devices and utilize some variation of equation (5). Also, they are usually very stiff such that stable, closed-loop force control becomes a challenge [16]. Since the type of admittance algorithm presented in this paper is trajectory-based, it avoids the problems associated with force control of a stiff system. Furthermore, there are a wide variety of robust feedback algorithms available in the literature for position control which can be easily implemented in a real-time environment [9].

Others ([14],[17] and [18]) have also found that the admittance control paradigm allows for a more intuitive and natural way to simulate the dynamics and kinematics of physical systems with haptic interface devices.

3 The haptic interface architecture

This section presents the underlying system architecture that is used. Again, the primary emphasis is on the utilization of readily available hardware. The human/device interaction forces are assumed to be available and measurable with a force transducer. Our particular focus is on the kinematic and dynamic analysis of mechanical systems. Based on the inertial characteristics of the virtual object with which interaction forces are to be simulated, a desired trajectory (including position, velocity, and acceleration) can be calculated. Tightly controlled end effector acceleration leads to accurate dynamic forces at the human/device interaction port. However, note that the forces and moments are not controlled directly, but rather serve as inputs to trajectory calculations. Errors in trajectory following will be manifested to the user as a deviation from the expected inertial characteristics of the object [15].

Hardware

Most haptic devices are either one-of-a-kind and/or very expensive to purchase making independent replication of results very difficult. This paper presents results obtained from experiments with a PUMA 560. This six degree of freedom manipulator has become a standard research tool for studying many aspects of robotics and is widely available.

The PUMA 560 is everything conventional wisdom says haptic interface devices should not be. It is highly geared, which leads to backlash, and it has a great deal of inertia and friction. (See [19] for parameters.) Its advantages are that it has a relatively large workspace and high force output capabilities. However, the potential for high force output presents safety concerns. Safety is an important issue with *all* haptic devices not just with systems based on industrial manipulators. Every effort has been made to ensure system safety by incorporating many of the procedures and precautions given in [20] and [21].

In light of the PUMA's apparent mechanical shortcomings, it would appear that this robot offers somewhat of a worst-case scenario. The presumption is that modern robots will exhibit better performance and that results presented here can only be improved upon. However, the PUMA's limitations should not be considered in and of themselves. Rather, what is important is the extent to which its control system can mitigate such effects as inertia and friction. The two extremes are building a mechanically perfect device versus building a controller which compensates perfectly for mechanical limitations. All haptic systems lie somewhere in between these two extremes.

The data acquisition components of our system are also readily available and relatively inexpensive. The LSI/11 VAL computer servo cards in the PUMA have been replaced with a Trident Robotics TRC004 general-purpose interface board which allows direct access to motor torques and encoders. A Trident TRC006 interface card serves as the I/O link between the TRC004 and a Pentium 166 Mhz personal computer. Watchdog timers are built into the system which shut down power to the robot in case of hardware or software crashes. The Pentium computing capacity coupled with the Trident system enables us to use fast servo loop update rates (typically 500 Hz or greater).

Force data is measured with an ATI force transducer type Gamma with a parallel port interface. Force sensing ranges are 133 N (30 lbs) in the x and y directions and 266 N (60 lbs) in the z direction. Torque sensing range is 11.3 N-M (100 in-lb) about all three axes. Force resolution is 0.11 N (0.4 oz) in the x and y directions and

0.22 N (0.8 oz) in the z direction. Torque resolution is 0.006 N-M (0.8 in-oz). Clearly the force transducer range and resolution will place upper and lower limits on the range of dynamic interactions we are able to simulate.

Software

Figure 1 presents the software architecture. Interaction forces are measured and input to rigid body mechanics simulation software which calculates position, velocity, and acceleration subject to pre-specified inertial characteristics. The simulation equations are integrated in time using a fourth-order Runge-Kutta algorithm.

A nonlinear computed-torque controller which includes time-varying gains and friction compensation is used in favor of the standard PUMA controller. The computed-torque controller is very effective at masking the PUMA's inertia and friction as perceived by the user. A quantitative discussion of the merits of this algorithm over the stock PID-based controller is beyond the scope of this paper. (See [9] for more details.)

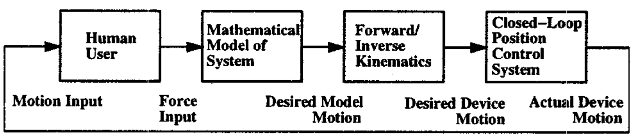

Figure 1: Haptic control system block diagram

We diverge from Reference [15] here in that the robot is controlled in joint space rather than directly in Cartesian space. Reference [15] avoids the inverse kinematic calculations relating Cartesian positions to joint positions but requires the Jacobian and its time derivative which enables the calculation of the inverse kinematic joint velocities and accelerations. The technique presented in [15] also requires computation of the inverse of the robot's inertia matrix and its mobility tensor. Clearly there is a trade-off between the complexity of the inverse kinematic solution for joint positions versus the inversion of these matrices. However, for robots with spherical wrist geometry and six or fewer degrees of freedom, the inverse kinematic calculations can be performed very efficiently.

4 An example: aircraft control column simulation

This section presents an example which illustrates the concepts discussed thus far. Specifically, a PUMA 560 is used to simulate the dynamics and kinematics of a two-degree-of-freedom aircraft control column with a human in the loop. This example illustrates the power of a haptic interface device as a design tool. New designs can be evaluated with a human in the loop by analyzing such things as ergonomics and dynamic loading at the base joint of the control column. A six-degree-of-freedom, general-purpose robot serves as a powerful design tool for studying human interaction with a physical system.

The basic mathematical model that the user interacts with is given by the following equations.

$$\begin{aligned} \left(I_{Z_1} + ML^2\right)\ddot{\theta}_1 + C_1\dot{\theta}_1 + \tau_{spr} &= -2LF_H \\ I_{Z_2}\ddot{\theta}_2 + C_2\dot{\theta}_2 + K_2\theta &= \tau_H \end{aligned} \qquad (6)$$

with the nonlinear rotational spring torque on joint 1 given by

$$\tau_{spr} = 2L\left(\frac{\gamma_1}{1 + e^{-\gamma_2\theta_1}} + \gamma_3\theta_1 - \frac{\gamma_1}{2}\right) \qquad (7)$$

where γ_i are user defined parameters. Note that this is a fourth-order, nonlinear system and that most haptic systems simulate only second-order, linear systems. Figures 2-5 present further details.

As the user interacts with the end effector of the PUMA robot, a force and torque is measured by the transducer and input into equation (6). The model is then numerically integrated in real-time to solve for the trajectory of the virtual control column in generalized coordinates. Forward kinematics equations then calculate the desired Cartesian position, orientation, velocity, and acceleration of the interaction port. The PUMA is then commanded to follow this trajectory using the closed-loop position control system presented in [9].

The admittance control approach presented here is very intuitive. The dynamics and kinematics of the haptic interaction port derive from straightforward mechanism equations of motion subject to user force and torque inputs.

The following figures present some experimental results for illustration purposes. The length dimension of the control column for this case is 2L, or 0.91 meters (3 feet). Figures 6-8 present results for the case when all spring stiffness and damping parameters are set to zero. Figure 6 illustrates the arc of travel of the PUMA as it follows the virtual control column's trajectory. Figures 7 and 8 present results for trajectory, force, and torque over selected time intervals.

The PUMA is capable of closely following the prescribed trajectory. The maximum errors occur when the load on the manipulator is greatest at 151 newtons.

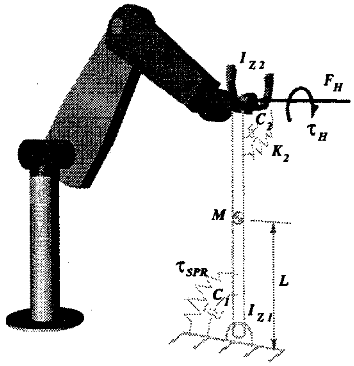

Figure 2: The PUMA 560 as a virtual aircraft control column mechanism

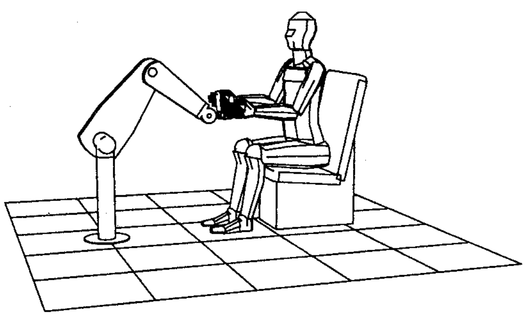

Figure 3: Conceptual schematic

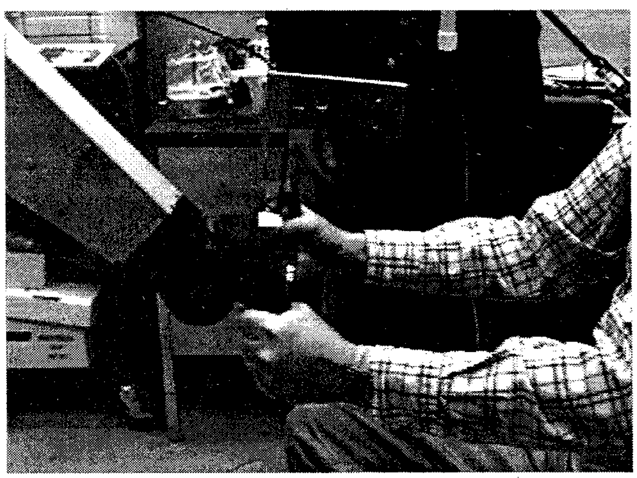

Figure 4: A user interacting with the PUMA and virtual control column

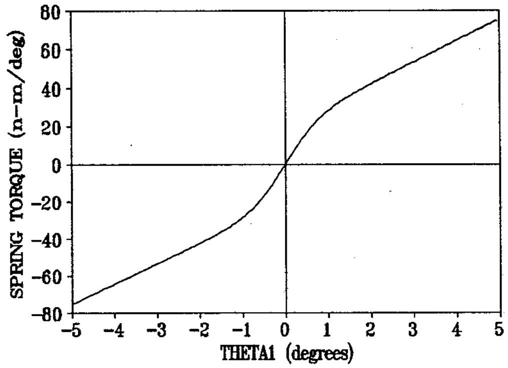

Figure 5: Torque versus deflection for the nonlinear rotational spring of Joint 1 of the virtual control column

Figures 9 and 10 present similar results with non-zero spring stiffness and damping parameters. Figure 9 shows the desired control column trajectory in joint coordinates and Figure 10 presents the resulting force and torque inputs.

Note that due to space constraints only position results are given here. Correct velocity and acceleration results have also been verified. Acceleration results were verified indirectly through forward kinematics calculations rather than through direct acceleration measurement. Future work will include validation with accelerometer measurements.

5 Conclusions

This paper presents an approach for haptic interface application development using off-the-shelf, general-purpose robotics hardware. An admittance control paradigm is used for developing an intuitive control system strategy based on measuring human user force/torque inputs and following prescribed motion outputs based on a governing model of the simulated system. Experimental results are given for a human-in-the-loop simulation of a two degree of freedom virtual control column mechanism. Also, users of this system report that the motion and "feel" of the device is quite good.

These results are encouraging and support the conclusion that general-purpose robots can be used successfully in many important haptic interface applications.

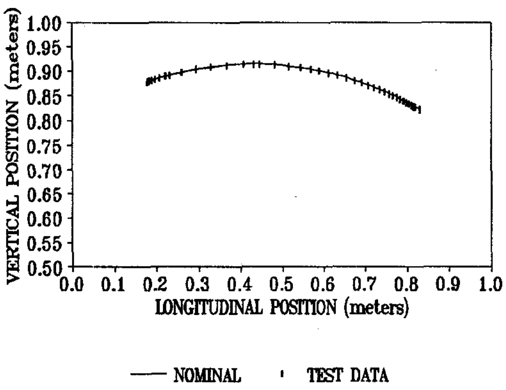

Figure 6: Virtual control column trajectory

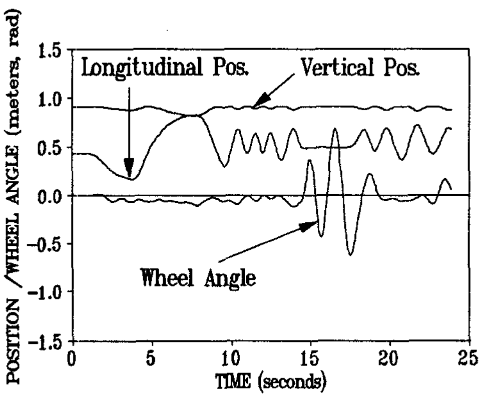

Figure 7: Virtual control column trajectory (time histories)

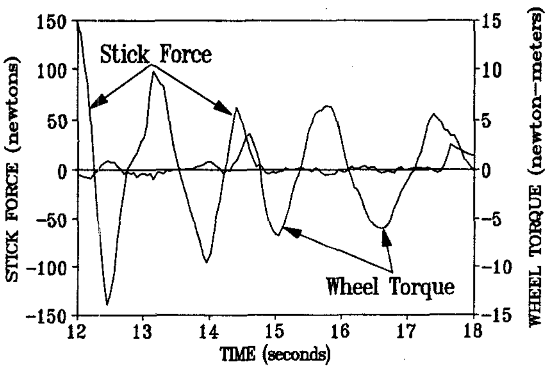

Figure 8: User force and torque inputs

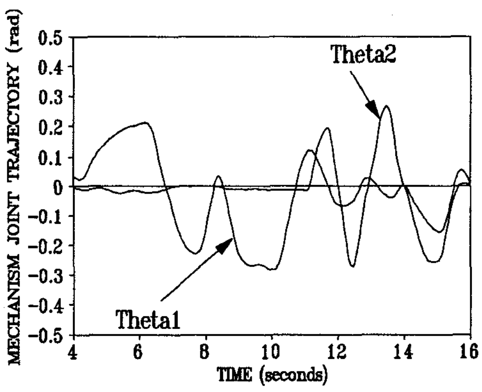

Figure 9: Desired mechanism trajectory in joint coordinates

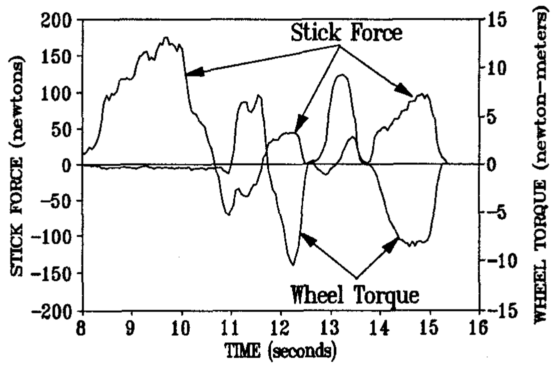

Figure 10: User force and torque inputs

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