Torque Feedback Control of Dry Friction Clutches for a Dissipative Passive Haptic Interface

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Abstract

The control of a passive dissipative haptic interface using electromagnetic dry friction clutches as actuators is considered. The performance of the device is currently limited by actuator performance. A dynamic simulation of the system indicates that actuator torque may be better controlled with torque feedback, resulting in improved path-following performance of the haptic interface. Experimental tests are presented which illustrate the validity of the simulation and the feasibility of implementing torque feedback control on the system's clutches.

1 Introduction

The haptic interface is a useful tool in many fields such as teleoperation, virtual reality, and assisted manufacturing. It serves as a tactile communication interface between man and machine by applying forces and/or torques to a human operator. Since a human is an inherent part of such a system, safety is a major concern, especially in applications where large contact forces are involved. Safety is a significant advantage of a passive haptic interface. These devices may only dissipate, redirect, and in some cases store energy applied by the user— they have no means of adding energy to the system. This attribute leads to more difficulty in control, as arbitrary control forces are not always achievable. This limits the range of haptic sensations that are possible with a passive device.

1.1 PTER – A Passive Haptic Testbed

A robot dubbed PTER (Passive Trajectory Enhancing Robot) was constructed to investigate the performance of passive dissipative haptic interfaces. Figure 1 is a diagram of PTER. The user interacts with PTER (and vice-versa) through the handle on the end of link D. PTER is a five-bar linkage having two degrees of freedom and four actuators, resulting in an overactuated system. The actuators are electromagnetic dry friction clutches. Clutch torque may be controlled by varying coil input current. Clutches 1 and 2 couple links A and B to ground, respectively. These clutches remove energy from the system. Clutches 3 and 4 couple links A and B together, in similar and opposite senses, respectively. These clutches transfer energy between links A and B. PTER has no energy storage devices. See [1] for a more detailed description of PTER.

1.2 Dynamic Simulation of PTER

PTER has been primarily used to study tip trajectory guidance. It is felt that system performance is currently limited by actuator performance, specifically by nonlinearities caused by friction. The discontinuous nature of friction forces makes precise control of the individual friction devices difficult. This paper addresses

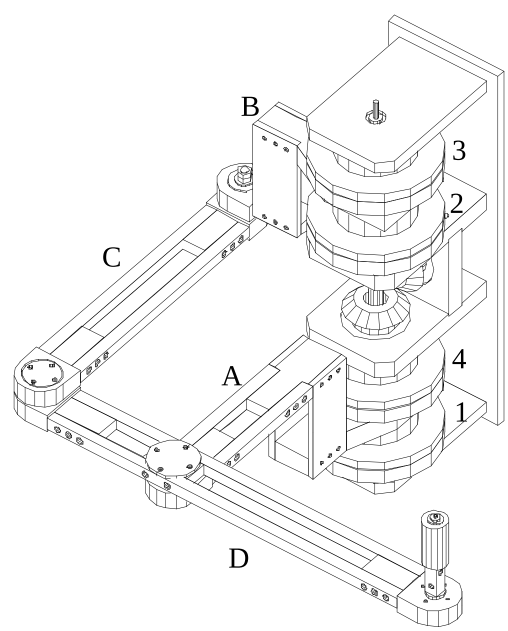


Figure 1: *PTER with clutch numbers and link letters*

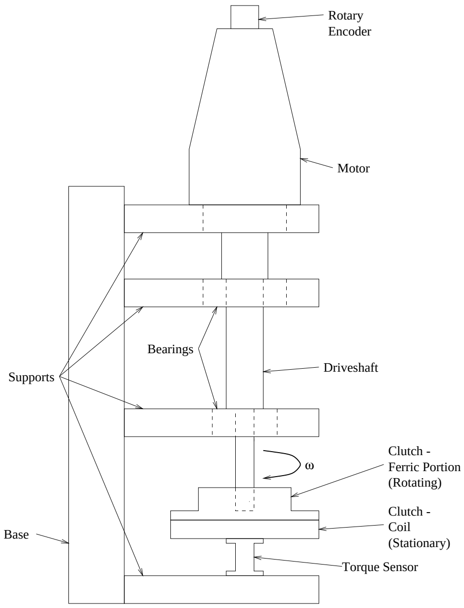


Figure 2: *Single Clutch Motorized Testbed*

the problem of more precisely controlling the friction-generated torques produced by PTER's clutches. A dynamic simulation of PTER including an actuator model was developed in order to evaluate the effect of new control concepts and clutch designs on system performance. [4] In short, the simulation utilizes PTER's inertial properties and computed net applied torque (comprised of actuator and operator effort) to solve the equations of motion for link accelerations, which are then integrated to obtain velocities and positions. The actuator model incorporates dynamic response and a numerical friction model.

Results from the simulation indicate that using torque feedback to control the clutches will improve the performance of PTER. [5] This will be discussed in more detail below. A new brake design which was expected to exhibit more favorable stick-slip friction characteristics has been considered, but a control-based solution utilizing the current clutches would be preferable.

1.3 Outline

Section 2 deals with the dynamic simulation of PTER. First, experimental data from a single clutch is compared with a single clutch simulation in order to verify the validity of the actuator model. Results of simulating PTER with a torque feedback controller will then be presented. In Section 3 an experimental torque feedback controller for a single clutch is explained and results are discussed.

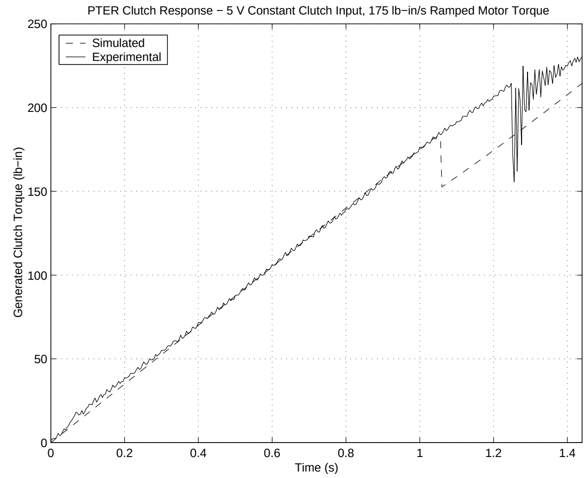


Figure 3: *Clutch Model Validation Tests - Stick-Slip Behavior*

2 Validation and Application of the Dynamic Simulation

2.1 Clutch Model Validation

In order to validate the accuracy of the simulation's actuator model, a single clutch testbed was built. See Figure 2 for a diagram of the testbed. A servomotor was used to provide a controllable input torque to the driveshaft. A reaction torque sensor was used to measure the torque transmitted by the clutch.

Two sets of tests were performed. In one test, the input current to the clutch (which effects clamping force) was held constant, and a ramped input torque was applied to the driveshaft by the servomotor. This test was used to compare the stick-slip transitions in the clutch and the simulation. Results of a typical test are shown in Figure 3. Initially the clutch is immobile, in a state of static friction, and the sudden drop in torque occurs at the breakaway point. Note that the breakaway torques of the actual clutch and the model are different. The clutch model is based on experimental data gathered from the testbed, but it is difficult to accurately model the friction characteristics. From test to test, the experimental torque values for a given clutch input current can vary significantly. The model does generally behave similar to the experimental response, however, exhibiting a drop in torque similar to the actual clutch. The main aim of the clutch friction model is to exhibit this effect. The oscillation seen in the experimental response is due to the construction of the testbed. The clutch coil assembly and torque sensor have relatively high torsional compliance, and the oscillation is due to stick-slip effects in the friction interface after the static-to-dynamic transition. The oscillations occur at approximately 95 Hz, which is the

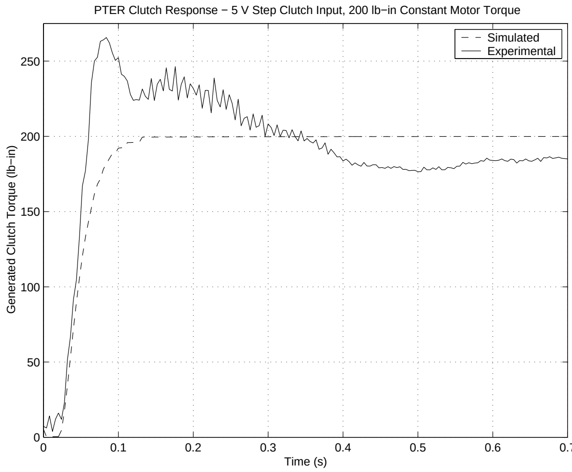


Figure 4: *Clutch Model Validation Tests - Dynamic Response*

natural frequency of the coil-sensor mechanical system. These oscillations will not be present when the clutch is installed on PTER, as the mounting geometry is much less compliant. Because of this, the oscillations are not modeled in the simulation.

The second test involved the dynamic response of the clutch. A constant input torque was applied by the servomotor, and a step input current was applied to the clutch at t=0. Figure 4 shows the results of a typical test. The response time of the actual and simulated clutches are similar. The steady-state dynamic torque values have some error, again due to difficulty in modeling friction characteristics as mentioned above. The overshoot in torque is due to the fact that a step is applied to the clutch from zero input current. At zero clutch current there is a slight gap between the two clutch plates and time elapses while the steel plate moves and makes contact with the coil. This leads to two effects— the time delay present in Figure 4, and the overshoot, caused by higher momentary normal forces which overcome the plate inertia, resulting in higher momentary clutch torque. Neither of these effects are observed if a step input is applied starting from non-zero input current, as the gap between the clutch plates has been closed prior to the application of the step.

2.2 Simulated Torque Feedback Control for PTER

In studying a possible alternative clutch for PTER, tests were performed in our lab which established that using torque feedback in a controlled friction device can improve torque following performance. Also observed was an ability to compensate for inprecise manufacturing which would normally result in a cogging effect— varying generated torque values dependent on

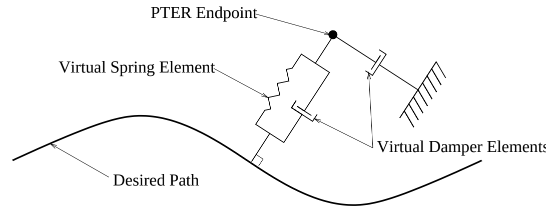


Figure 5: *Impedance Controller - Virtual Elements*

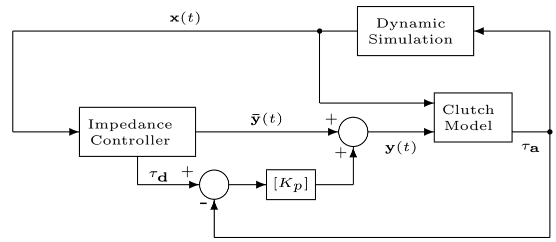


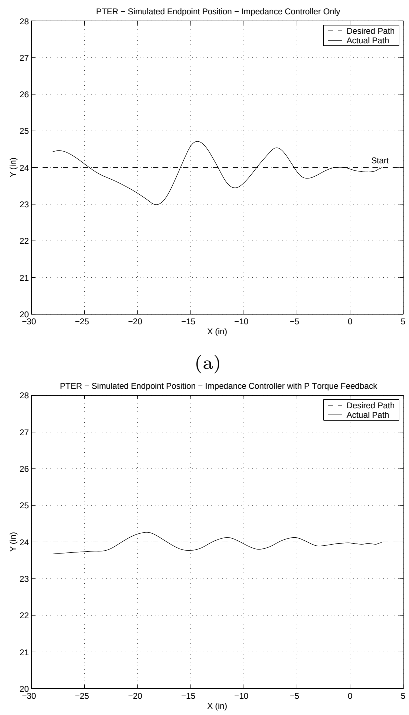
Figure 6: *Modified Impedance Controller with Torque Feedback*

clutch position. [3] It was decided to investigate torque feedback control of PTER's existing clutches with the goal of improving torque following performance. We thought that this would ultimately improve PTER's path following performance.

The controller presently employed on PTER is a position error impedance controller, which attempts to constrain PTER's endpoint to an arbitrary path. The error signal is defined as the perpendicular distance between the desired path and the endpoint position. Desired endpoint forces are calculated by simulating a virtual spring and damper between the endpoint and the desired path. See Figure 5 for a diagram of these virtual elements. The desired endpoint forces thus calculated are then used to calculate a set of desired clutch torques. A look-up table is used to convert clutch torques to clutch input currents.

A standard test was defined for the simulation. In this test, the goal of the controller was to keep PTER's endpoint constrained to a straight line in its workspace (the desired path.) Input force to the tip consisted of a force parallel to the desired path, and a time-varying force (a sum of several sinewaves) tangent to the desired path. The performance of the device is measured by how well the endpoint is constrained to the desired path. Figures 7(a) and 8(a) show the simulated track of PTER's endpoint using the impedance controller, as well as a graph of the torque produced by a single clutch during the simulation.

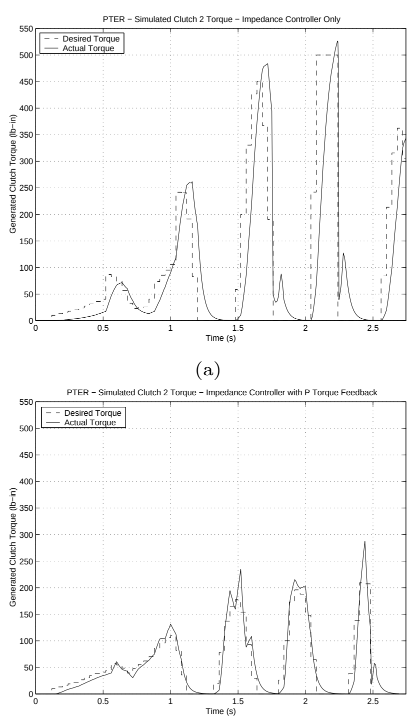
To test the effect of torque feedback control on PTER's path following performance, a proportional feedback



(a)

(b)

Figure 7: *Simulated Performance of PTER - endpoint position with (a) LUT and (b) LUT with feedback*



(a)

(b)

Figure 8: *Simulated Performance of PTER - generated clutch 2 torque with (a) LUT and (b) LUT with feedback*

controller was added to the existing impedance controller in the simulation. Figure 6 is the modified controller block diagram. Gain tuning was done by performing a battery of line following simulations at different values of K_p. An appropriate gain was chosen that exhibited satisfactory improvements in performance without saturating the actuators. Figures 7(b) and 8(b) show the results of the line following test using the modified impedance controller at this gain.

Figures 7 and 8 show a clear reduction in path following error when torque feedback is introduced. Time average path error with no feedback is 0.34 in, versus 0.13 in with proportional feedback. Note also the improvement in torque following performance that the feedback controller yields, as well as the lower overall torque levels requested by the controller. This is due to the lower average position error, which reduces the force required by the "virtual spring" in the impedance controller.

3 Torque Feedback Control of Friction Clutches

3.1 Experimental Setup

As shown above, the simulation of PTER suggests improved performance when torque feedback is integrated into the controller. In order to evaluate whether or not torque feedback control of PTER itself would be feasible, we decided to implement a torque feedback controller on a single clutch.

The same motorized testbed used in the above clutch validation tests was used for this experiment. The control system consisted of a dSPACE DS1102 board, which contains A/D and D/A converters and a Texas Instruments DSP processor. The controller implemented was similar to the one illustrated in Figure 6, except a predefined desired torque profile was used instead of impedance modeling used to calculate PTER's desired clutch torques. The controller sampling rate was 1 kHz.

Tests were run with two desired clutch torque profiles. The first was a rectified sine wave. The absolute value of the sinewave was used in order to keep the desired torque value positive at all times. The second profile is a desired torque profile calculated by the full simulation of PTER. It was thought that such a profile would most accurately represent desired torques required of the clutch in actual operation in PTER.

3.2 Results

3.2.1 Sinewave Torque Profile: Figure 9(a) is a plot of open-loop sinewave following performance

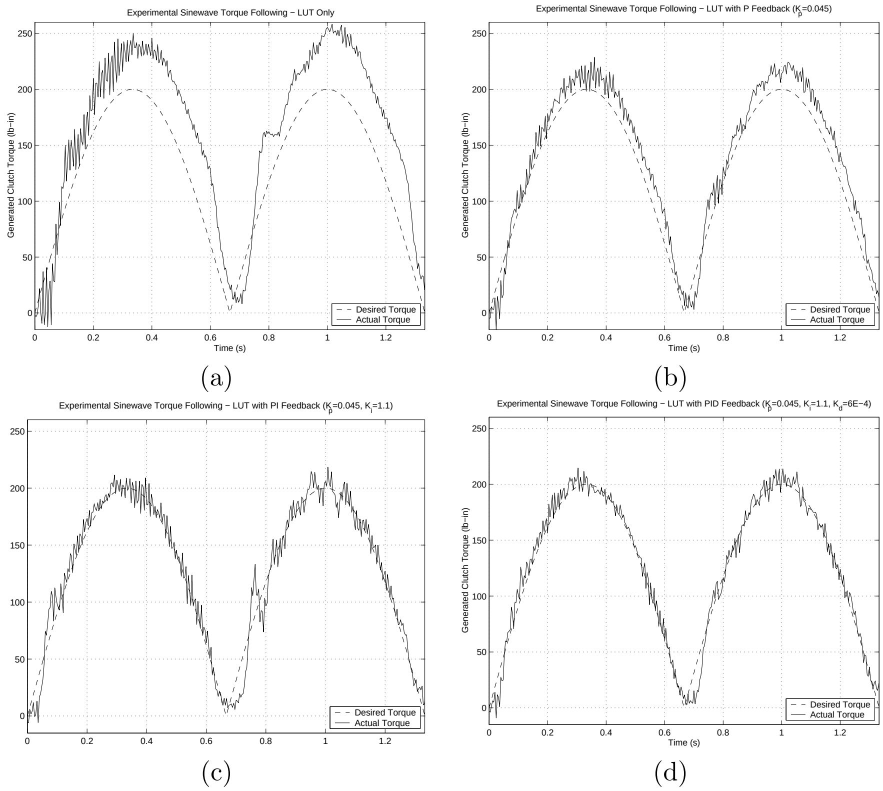


Figure 9: *Experimental Single Clutch Sinewave Following Response - (a) look up table only, (b) P feedback, (c) PI feedback, (d) PID feedback*

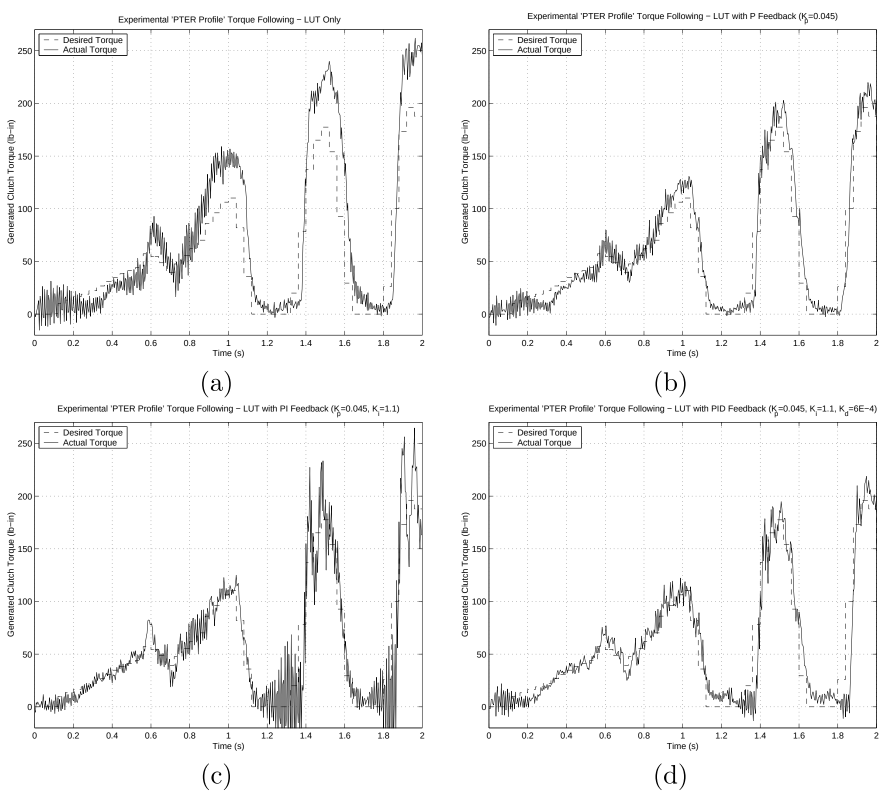


Figure 10: *Experimental Single Clutch "PTER Profile" Following Response - (a) look up table only, (b) P feedback, (c) PI feedback, (d) PID feedback*

of a single clutch. In this test, only the torque-to-current look-up table was used to compute clutch input current. The high frequency vibration occurs at approximately 95 Hz and is attributable to the compliance in the torque sensor as discussed in section 2.1 above. Adding a P feedback loop to the look-up table yielded the performance shown in 9(b). Note that the tracking error is reduced, but is still nonzero. Also, the controller, running at a speed an order of magnitude higher than the natural frequency of the torque sensor-clutch coil system, appears to attenuate the 95 Hz vibration seen in Figure 9(a). Figures 9(c) and 9(d) represent the performance of PI and PID controllers, respectively. The integral effect of each of these controllers drive the average tracking error more nearly to zero. The PI controller exhibits some overshoot-driven oscillation, most apparent in the second half-wave. The derivative term in the PID controller compensates for this effect.

Note that each of the four controllers exhibit a finite time delay at the two points in the torque profile where desired torque increases rapidly from zero. This is similar to the time delay observed in the step-input tests discussed in the previous section, and represents the time required by the clutch plate to move and make contact with the friction surface on the coil.

In comparing the results of the look-up table based controller and the feedback controllers, it is clear that torque feedback control of PTER's clutches is not only feasible, but can yield large improvements in torque following performance. At this point, the PID controller looks like the best performer of the three, yielding low overshoot, satisfactory response time, and low average tracking error.

3.2.2 Simulated PTER Torque Profile: Figure 10 shows results of using the four controllers described in the previous section to follow the typical PTER profile generated by the PTER simulation. Similar behavior is observed for this profile as was seen in the sinewave profile. However, note in Figure 10(c) that the PI controller exhibits high overshoot during sharp increases in desired torque. Again, the derivative term of the PID controller serves to attenuate this. The torque-following performance of the P and PID controllers are roughly similar, having time-average torque errors of 12.1 and 11.9 in-lb, respectively. The open-loop and PI controllers had average errors of 25.3 and 16.1 in-lb, respectively.

The results presented above for the sinewave test are encouraging, but such a profile would rarely be desired on the actual device. The results of the simulated profile tests show that torque feedback still improves torque following performance for a profile that more nearly matches those that will be seen on the actual device.

4 Conclusion and Future Work

Three points have been illustrated by this work. First of all, the actuator model within the dynamic simulation of PTER is a valid representation of the dominant friction effects present in the clutches. This was shown through comparisons of experimental and simulated tests. Secondly, the simulation indicates that the addition of torque feedback to PTER's controller will improve path following performance. Finally, it was shown that torque feedback does in fact improve torque following capability of our controlled friction device in an experimental setup. These points lead to the conclusion that using torque feedback in PTER's controller should improve its performance.

In order to implement such a controller, the torque generated by each of PTER's four clutches must be measured. This capability is not possible with the current design. A modified clutch which has integrated torque measuring capability has been evaluated and is currently being put into service on PTER. The torque feedback controller discussed in this paper will be implemented, as well as several other higher-level control concepts that may improve on the performance of the impedance controller. System identification tests as well as controlled-input experiments will be performed in order to validate and improve on the full-scale simulation of PTER.

Acknowledgments
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