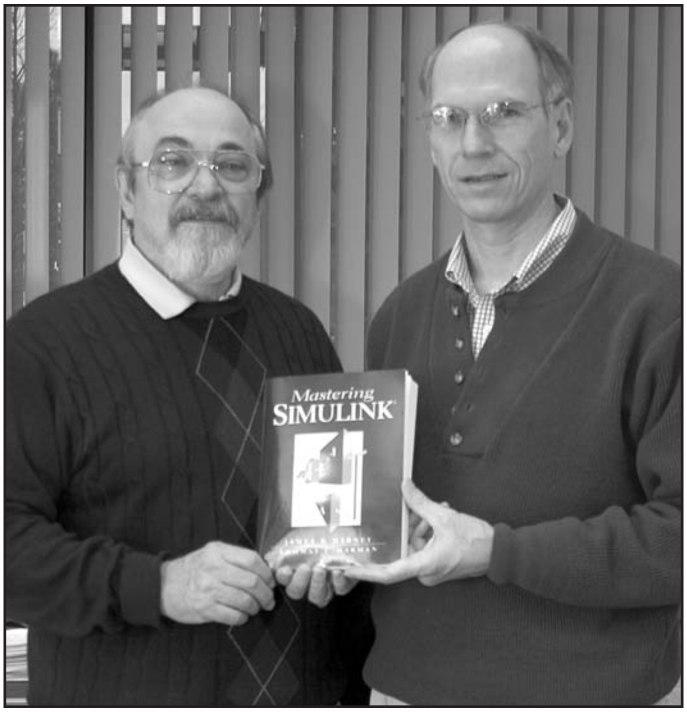
Real-Time Active Loading of Piezoelectric Ultrasonic Motors for Simulating Space Robotics Applications

by James B. Dabney and Thomas L. Harman

ABSTRACT—The next generation of robotic spacecraft will require simple, reliable, and lightweight robotic manipulators. This research enabled a new class of robotic actuators by successfully producing a prototype real-time model-based torque control system for a piezoelectric ultrasonic motor. Piezoelectric ultrasonic motors (PUMs) offer dramatic improvements to a variety of space-based robotics applications, if the problem of real-time torque control can be solved. This research used the UHCL PUM laboratory apparatus to develop, implement, and experimentally validate a real-time model-based PUM torque control law.



PROGRAMMING—Thomas L. Harman, (*l.*) and James B. Dabney hold a copy of the new edition of their book, *Mastering Simulink*.

SPACE-BASED ROBOTS TYPICALLY REQUIRE ACTUATORS WITH the advantages of high precision, light weight, and simplicity. Piezoelectric ultrasonic motors (PUM) are well-suited to these requirements. PUM can achieve high precision as a result of low speed, its lack of gears and transmissions, and the freedom it affords from backlash. They are quite simple mechanically, consisting of a single moving part that provides the same functionality as motor, transmission, and brake in a conventional motor-driven system.[1]

A typical piezoelectric ultrasonic motor (Piezo Systems/Shinsei USR 30, Fig. 1)[2] consists of a toothed piezoelectric disk (stator) in contact with a metal disk (rotor). Time-varying electric fields applied to the piezoelectric stator induce a traveling wave which is mechanically rectified, causing the rotor to rotate (Fig. 2).[3] This mechanism produces relatively high torque at low rotor angular velocities, obviating the need for gearing. The friction between rotor and stator provides a passive holding torque typically larger than the rotating torque, eliminating the need for mechanical brakes or active holding torque. These motors can be built such that they neither produce nor are affected by magnetic fields, making them useful in highly magnetic environments and applications in which magnetic fields are harmful.

The state of the art in control of PUM was not fully developed prior to this work. Good results had been achieved for applications requiring only speed regulation. Also, existing controller technology was adequate for positioning applications traditionally served by stepper motors. The new UHCL model-based torque control algorithm addresses the many important potential PUM applications requiring precise torque control.

Goals of the Project

The ultimate goal of the PUM research conducted in the UHCL Systems Engineering Laboratory was to develop a PUM driver/controller unit that implements model-based real-time torque control algorithms. The goal was achieved this year in the form of a prototype driver/controller which implemented a model-based control law developed in the Systems Engineering Laboratory of the University of Houston-Clear Lake.

Results

PUM hardware is shown in Fig. 3. The PUM is mounted to a torque sensor and drives a flywheel which, in turn, drives a magnetic particle brake. The brake is connected by a flexible coupling to a laser encoder which measures the motor angular position. The magnetic particle brake produces a brake torque commanded by the dSpace software system. A system block diagram including the magnetic particle brake and driver is shown in Fig. 4.

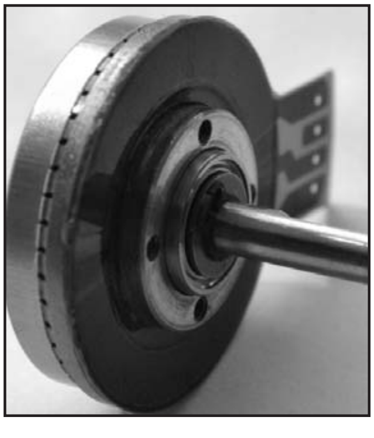


Figure 1. Piezo Systems Ultrasonic Motor (Shinsei USR30)

Previously, the experimental apparatus was used to characterize the relationship among drive signal frequency, motor speed, and motor torque, resulting in the torque surface shown in Fig. 5. A control law was imple-

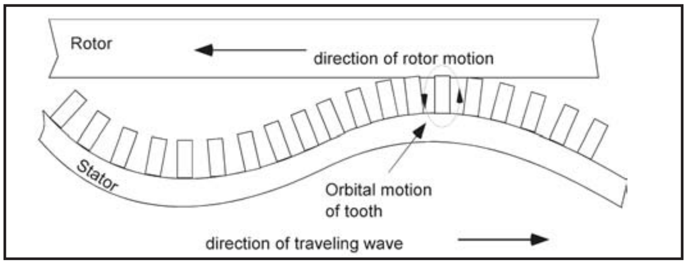


Figure 2. Traveling Wave Formation

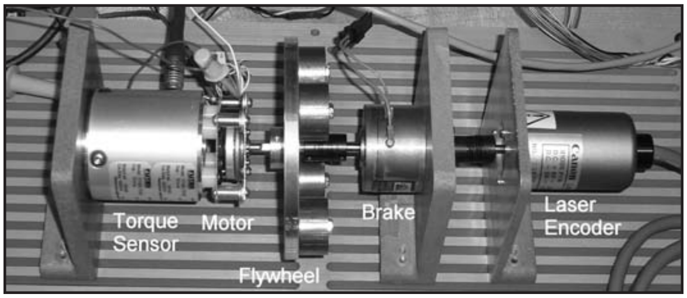


Figure 3. Motor and Encoder Assembly

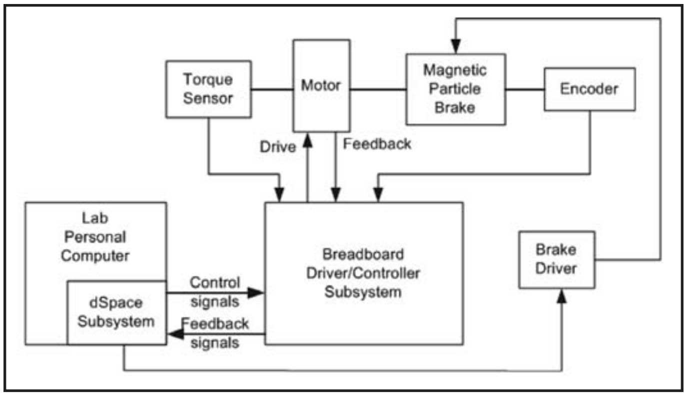


Figure 4. Apparatus Schematic

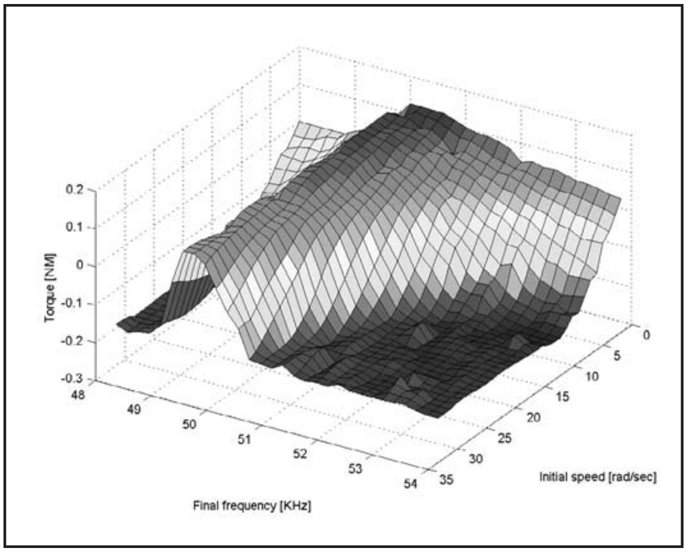


Figure 5. Example PUM Torque Surface

mented that inverts the torque surface shown in Fig. 5 to compute drive signal frequency as a function of instantaneous motor speed and commanded torque. The control law was implemented using the Simulink4 model shown in Fig. 6 and loaded into the dSpace real-time control system. Regulation and tracking experiments were performed to demonstrate that the control law is effective throughout the PUM operational range. Example tracking experiment results are shown in Fig. 7.

In the tracking experiment, the control objective was to maintain constant torque magnitude of 0.01 NM, switching torque sign at +/-10 rad/sec. The brake torque was set to its residual value of 0.00015 NM (the brake produces approximately 0.00015 NM of drag torque when not energized). Examining Fig. 7, it is apparent that the motor torque deviates from commanded torque twice during each branch of the speed trajectory. The first deviation occurs when the commanded torque changes sign and is relatively small. The second deviation occurs when the motor direction of rotation changes sign and consequently when the motor switches from a braking mode to an accelerating mode. A factor that degraded tracking performance somewhat was drift in drive signal amplitude each time the drive signal phase (sense) switched. It is expected that an improved controller with more stable voltage regulation and greater frequency precision will improve tracking accuracy.

Conclusions and Future Work

This work has demonstrated the feasibility of model-based torque control for an important class of traveling wave piezoelectric ultrasonic motors. The model-based torque controller provides stable torque control at constant motor speed and convergent tracking during transient operation. The operation of the algorithm was demonstrated by simulation and experimention.
Future work will entail development of a single degree of freedom haptic display using the present apparatus. The torque control performance can be improved by higher bandwidth control and increased resolution of frequency control.

Acknowledgments

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[3] N. W. Hagood and A. J. McFarland, "Modeling of a Piezoelectric Ultrasonic Motor," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 42.2 (1995): 210-31.

[4] J. B. Dabney and T. L. Harman, *Mastering Simulink*. Upper Saddle River, NJ: Prentice-Hall, 2004.

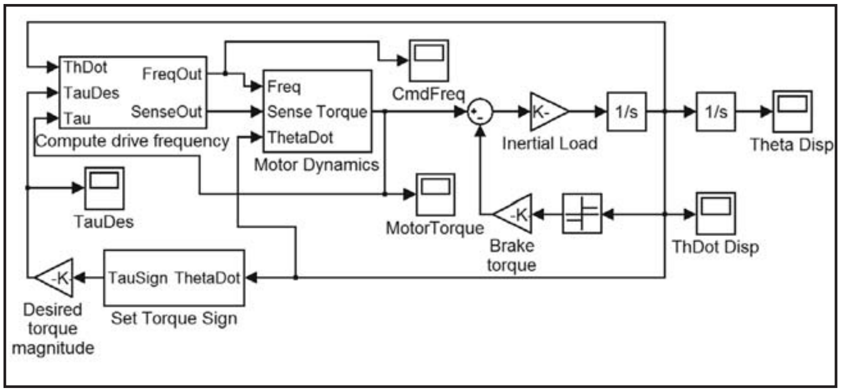

Figure 6. PUM Simulation Implementing Model-based Torque Control

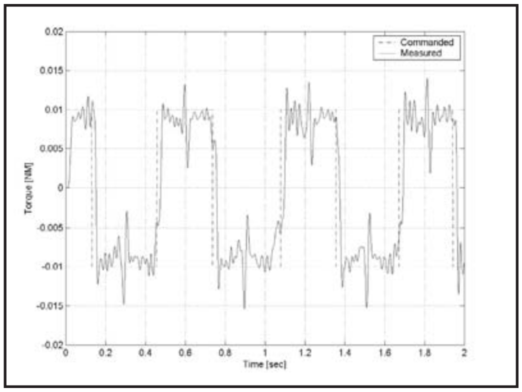

Figure 7. Tracking Response Using Model-based Torque Control

Publications

Dabney, J. B., T. L. Harman, F. H. Ghorbel, C. Aswatharanayan, M. Randolph-Gips, and J. J. Chakkungal. "Dynamic Response Modeling of Piezoelectric Ultrasonic Motors," 2005 International Mechanical Engineering Conference and Exhibition, Orlando, FL, 2005.

Dabney, J. B., T. L. Harman, F. H. Ghorbel, and J. J. Chakkungal. "Model-Based Torque Control of Piezoelectric Ultrasonic Motors," International Mechanical Engineering Conference and Exposition, Chicago, IL, 2006.

Dabney, J. B., and V. Tang. "Model-based Torque Control of Piezoelectric Ultrasonic Motors," STTR Phase I *Final Report*, UHCL Systems Engineering Laboratory, 2005.

Presentations

Wagner, C., J. Arceneaux, A. Vyvial. "Model-Based Torque Control of Piezoelectric Ultrasonic Motors," Capstone Project Report, UHCL Systems Engineering Laboratory, 2005.

Funding

Dabney, J. B. "Model-Based Torque Control of Piezoelectric Ultrasonic Motors." January, 2005, $600,000. (*Not funded.*)

Dabney, J. B., "Robust Miniaturized Piezoelectric Motor Controller," September 2005, $100,000. (*Not funded.*)

Dabney, J. B., T. L. Harman. "Low Cost Haptic Display Using Piezoelectric Ultrasonic Motors," Texas Advanced Research Program, February 2006, $66,000. (*Not funded.*)

STUDIES—Teamwork is an essential part of any research effort, exemplified by these students at work in the Bayou Building at UHCL.