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# Design and modeling of a flexible test bed for use in control system analysis and verification

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#### Abstract

This paper describes a test bed specifically designed for studying the effects of nonlinear friction, backlash, and drive train flexibility on structurally flexible electro-mechanical systems, and for developing control algorithms that will compensate for nonlinear friction, backlash, and drive train flexibility in structurally flexible electro-mechanical systems. The test bed has a modular and adjustable design. Friction, backlash, and flexibility can all be varied or disabled. A mathematical model of the dynamics of the test bed is also described. This model includes stiction, Coulomb friction, backlash and drive train, and link flexibility. The model is verified via comparisons of model-predicted and experimental responses. © 2002 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

A control system design for real world mechanical systems is complicated by nonlinear phenomena such as stiction and backlash. A common approach is to overdesign a controller, based on a linear model, in anticipation that the controller performance will degrade in the presence of the unmodeled nonlinearities. There are several difficulties with this approach. First, the overdesigned controller often requires higher bandwidth than a design which directly accounts for nonlinearities, resulting in higher actuator costs. Second, this approach assumes that the controller

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will be robust with respect to the unmodeled nonlinearities. In many cases, the resulting system is stable, but exhibits limit cycle behavior. This is common, for example, with integral controllers where the real world system has stiction. A better approach is to design the controller to directly account for system nonlinearities. The true test of a control system comes when it is implemented and run on actual hardware. For these reasons, hardware designed and built specifically for testing control system algorithms and studying the effect of nonlinear phenomena, is important in control system research.

Several researchers have published their designs for hardware built for testing control systems in the presence of nonlinearities. Two notable designs were published by Prakah-Asante et al. [1] and Mattice [2]. The hardware described by both authors includes mechanisms for introducing variable backlash, friction, inertia, and flexibility. Prakah-Asante's design was developed for university research and instruction. Mattice's hardware was developed by the US Army to test control algorithms for gun turrets. While both devices provide a good test bed for verifying control system performance, neither was built specifically for studying mechanical backlash, stiction, or Coulomb friction, and their effects on controller designs.

The Friction and Backlash Test Bed (FBTB) described in this paper was specifically designed for studying the effects of nonlinear friction and backlash on control systems and to test new control algorithms that can account for these phenomena. Our system shares some similarities with designs previously published by Prakah-Asante et al. [1] and Mattice [2]. It includes variable backlash, friction, inertia, and flexibility mechanisms. Unlike the other designs, it also includes an accurate mathematical model which accounts for Coulomb friction, stiction, backlash dynamics, and system flexibility. This provides the opportunity to study these phenomena from a theoretical, as well as an experimental viewpoint.

The remainder of this paper is divided into three sections. In Section 2, we describe the FBTB and its components. In Section 3 we present our mathematical model of the test bed and compare model-predicted to experimental results. Conclusions and recommendations are discussed in Section 4.

### 2. Hardware description

The FBTB is shown in Fig. 1. It includes an interchangeable flexible link that slides over the smooth surface of a large granite table. The tip of the flexible link is attached to an air cushion support that reduces the contact friction to a very low level. The flexible link is actuated via a direct drive torque motor in series with variable backlash and friction mechanisms. Optical encoders measure the angular positions of the shafts on each side of the backlash and friction mechanisms. An overhead infrared sensor measures the link's tip position. The entire system is connected to a dedicated signal processing unit and a Sun SPARCstation running Real-Time Innovation's ControlShell development software [3]. A system schematic is shown in Fig. 2. Individual FBTB components are described in the following paragraphs.

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