Development of an Eddy-Current Actuator Test Bed

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There is no simple, inexpensive yet extensible test bed for simulating microgravity. This is a large technological gap in the development of space systems at the level of universities, small companies and individuals. Experimental validation of eddy-current interactions in a prototype contactless actuator provided the motivation for design of a new 1-D low-friction test bed. This paper describes the design and development of a low-cost, 1-degree-of-freedom experimental test bed with closed loop actuation overseen by Simulink. The system can support many different experiments that require microgravity and closed-loop control.

I. Introduction

Both public and private sectors have expressed interest in missions to rendezvous and manipulate an uncooperative target using a chaser spacecraft. These operations are inherently risky for both the target and the chaser spacecraft due to the nature of uncooperative targets in the space environment. The dynamics of the target can be unpredictable in 6 degrees of freedom, there is no natural damping, and the non-compliant nature of a rigid gripper grabbing a rigid target leaves little room for error. The mature technologies currently available leave much to be desired in terms of risk mitigation. The shortcomings of current technologies and operational risks make a contactless actuator an attractive addition to a spacecraft designer's toolbox. A future contactless actuator could use eddy-current forces to interact with a target. This technology is immature and a low-friction test bed is critical to eddy-current actuators developing into a mature technology. Most low-friction test beds have a number of disadvantages that make them unsuitable for some applications, including the experimental verification of a prototype eddy-current actuator. Motivated by these experiments, this paper describes the requirements and architecture of a low-cost, extensible, low-friction test bed.

II. Background

A. Low-Friction Test Beds

Several versions of low-friction test beds are already available for spacecraft research, each with their own advantages and disadvantages. The two most common alternatives to the test bed in this paper are air-bearing test beds and rotational test beds. They have a number of advantages. However, unnecessary degrees of freedom, cost, complication and lack of extensibility motivated the construction of a 1-DOF air-track test bed.

Air bearing test beds have simulated microgravity dynamics, both translational and rotational, for over 45 years.[1] Traditional planar air bearing systems are ideal for testing 2-DOF dynamics, but have a number of drawbacks that make them unattractive for testing 1-DOF systems like early-stage eddy-current actuators. The second degree of freedom introduces extraneous variables when testing 1-DOF systems. Sensing the state of the 2-DOF system in real-time requires video processing software that is either custom built or expensive.[2] Closed loop control requires on-board computing, adding to the complication of the system.[3] Planar air bearings require extremely flat surfaces and rapidly consume compressed gas canisters.

Rotational test-beds can also simulate1-DOF microgravity dynamics. These test-beds consist of a target on the end of a long arm attached to a low-friction rotational axis.[4] The throw over which they can approximate linear translation is limited by the length of the arm. The bearings holding the rotational axis experience more off-axis torque as the arm length increases so the friction will increase with the throw of the system. This connection

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between friction and throw length is the primary downside for eddy-current experiments, which require a large variation in the throw of the system.

B. Eddy-Current Actuators for On-Orbit Servicing

Experimental development of eddy-current actuators motivated the development of the test-bed, but the reader may wonder what motivates the need for eddy-current actuators. In short eddy-current actuators could provide a technological capability that does not currently exist: the ability to physically interact with a macro-scale, uncooperative target in orbit. This ability would be particularly helpful to on-orbit servicing missions because they entail the close interaction of two spacecraft who were not originally designed to interact.[5] Eddy-current actuators could allow a large spacecraft to safely manipulate the dynamics of an uncooperative target or allow a small spacecraft to maneuver near a large target without fuel.[6] Studies of eddy-current actuators have not investigated their orbital applications, instead focusing on levitation[7] and active damping.[8] An experimental test bed will help to bridge this gap that exists both in the literature and spacecraft capabilities.

III. Test Bed Requirements

A low-friction test bed with a versatile closed-loop controller will enable experiments that are essential for transforming EC actuators from a promising concept to a functional technology. This section outlines the capabilities that make the test bed system necessary for EC actuator development and the requirements on the system in order to provide these capabilities. An additional advantage of this test bed is its use of inexpensive off-the-shelf parts and software.

A. Justification for Test Bed Experiments

Experiments performed on a low-friction test-bed integral to the development of EC actuators. The literature fails to address eddy-current forces that produce controlled actuation forces on a remote moving target. EC actuators will operate in dynamic conditions that present numerical and analytical challenges for the simulation, analysis, and validation of EC-based control without experiments.

The equations governing the formation of currents by a changing magnetic field are essentially a vector form of the heat equation. This means that the forces produced by these interactions are impossible to find analytically except in a few constrained cases. Any useful actuator would need to operate outside of these cases. Numerical models could find the forces, but there are problems with this approach as well. It is difficult for finite element models to accurately incorporate both a non-steady-state external magnetic field and the dynamics of the target. Traditional FEM models are also specific to each actuator configuration. This makes it hard to iterate quickly and build intuition about a new technology. Inevitably, these models must be simplified, but it is not yet clear which assumptions can even be made. The development of a working EC actuator needs validation of design choices and control systems beyond that is beyond the capabilities of numerical simulations.

Testing EC systems on a low-friction test bed has advantages over analytical and numerical models in several ways. Experimental characterization bypasses unmodeled effects that can be created by the many nonlinearities in the system. Experiments on a complete system will build valuable intuition for designing the prototype actuator. A physical demonstration of the capabilities of EC forces for actuation is far more compelling than models. Finally, the development of the test bed necessary for experimental characterization will give the capability to verify future models and test prototypes of both actuator hardware and control systems.

B. Minimum Requirements for Success

The test bed needs to meet a number of requirements. These requirements can be broken down into three broad categories:

1. Sensing Capabilities
2. Actuation Capabilities
3. Extensibility

Accurate system characterization and closed loop control both require ability to measure the full state (acceleration, velocity, and position) of the target cart during an experiment. The need for accurate time-varying measurements of the target's state imposes a number a design constraints that are simple in concept, but non-trivial to implement. In order to capture the dynamics of the target, the frequency of state measurements needs to be at least 10x the dominant dynamics exhibited by the target under normal operating conditions. Additionally, the resolution in position needs to be fine enough to capture small changes in the position. Finally, state measurements need to be consistently accurate over the course of an experiment – the system will need to compensate for sensor drift.

Quality measurements are not useful without the ability to produce controllable outputs and measure the state of actuator producing the forces. In order to create forces large enough to measurably affect the target, the actuator needs to produce at least two independent sinusoidal magnetic fields whose properties vary with time. The magnetic field is generated by the current through the electromagnet. As the control input (U) to the system, the currents through the electromagnets should be both measureable and controllable (in a practical rather than formal sense.)

A goal of the test bed development was also to keep costs low and both the extensibility and reproducibility of the system high. In order to achieve this flexibility, the components of the system should be easily replaced and upgraded to fit the current experiment. The target cart should be able to accept targets of different sizes and materials, with the ability to hold them in different orientations so that the actuator can be validated in different scenarios. Additionally, reconfiguring the physical setup of hardware should be simple – different experiments require different setups and the design of the prototype can change frequently based on new information. This places a requirement on the computing capabilities of the system: it needs to be able to accept sensor signals as analog voltages and output analog voltages to the actuators. This allows the sensors and actuators to be mutable based on the demands of the experiment.

IV. System Architecture

The test bed consists of four subsystems. The track-cart subsystem includes all of the moving parts and the air track that supports them. The sensor subsystem comprises the sensors that measure the physical state of the system. The actuator subsystem contains the electromagnets that generate the actuating magnetic field as well as the power supply. The sensor and actuator subsystems connect to the computer subsystem that serves as the "brain" of the entire system – recording data, estimating the state of the cart from the sensor inputs and closing the loop between the sensors and the actuator.

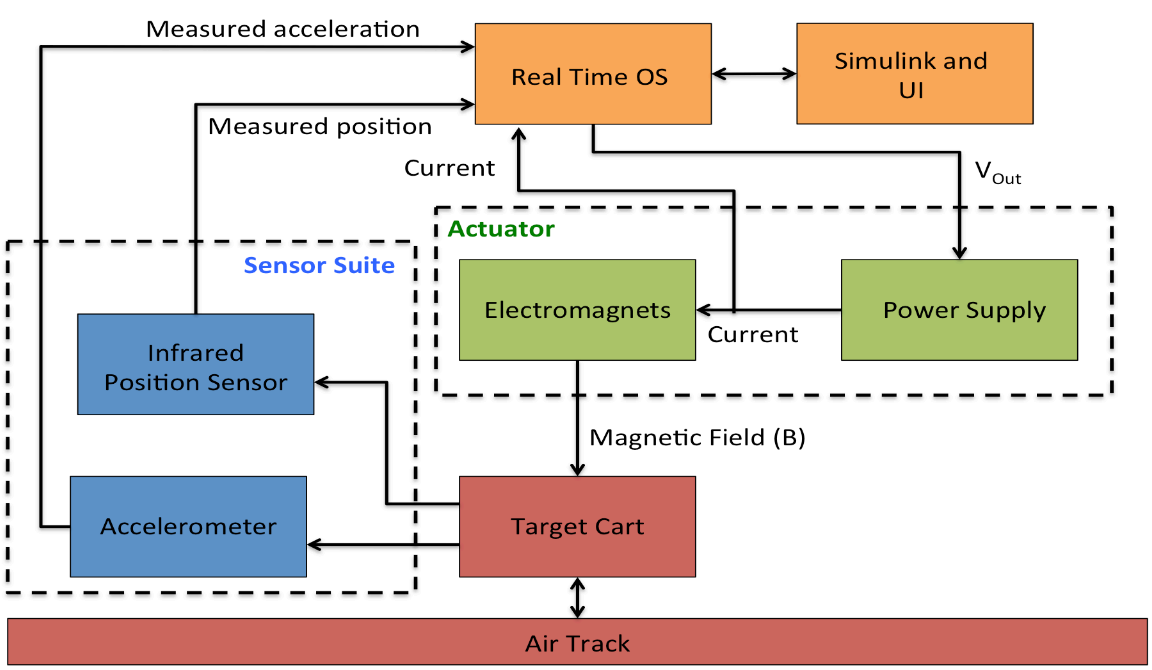

Figure 1: System architecture diagram illustrating the flow of information between components of the test bed. The track-cart subsystem is on the bottom, the sensor subsystem is on the left and the actuator subsystem is in the upper-right.

A. Track-Cart Subsystem

The track cart subsystem is a heavily modified Pasco Scientific low-friction air track that is powered by a standard compressed air line. The track allows the target cart to exhibit low-friction dynamics similar to those found in a micro-gravity environment. The single degree of freedom is beneficial because it simplifies the sensors necessary to measure the state of the system and simplifies the system for experiments that verify models or test parameter sensitivity.

Several modifications to the standard carts improve the extensibility of the system. Machined mounting points and modular mounting brackets enable the carts to accept any payload with the correct screw through-holes, making the carts able to accommodate future experiments that may have different payload requirements. The target mount is n front of the cart to ensure that the primary eddy-current interactions are between the actuator and the target, rather than the cart itself. Counterweights that are adjustable in directions both parallel and perpendicular to the axis of the cart prevent unbalanced loads from introducing friction into the system.

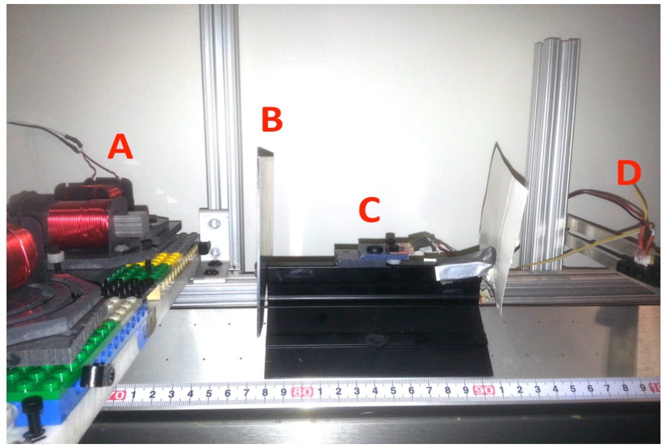

Figure 2: The test bed. Visible components: Actuation magnets (A); Cart (C) with accelerometer and conductive target (B); IR position sensor (D) on far right.

B. Computer

The core of the computer subsystem is a host computer running windows/Simulink and a target computer running the Simulink xPC Target real-time operating system. The real-time target handles analog to digital and digital to analog conversion (ADC and DAC) through a NI PCIe 6000 DAQ card. The real time target runs the Simulink diagram shown in figure 4 in a discrete loop with a 0.00025 second step size. This step size corresponds to a loop frequency of 4000 Hz, which exceeds the maximum frequency of the actuator (200 Hz) by more than an order of magnitude, allowing the system

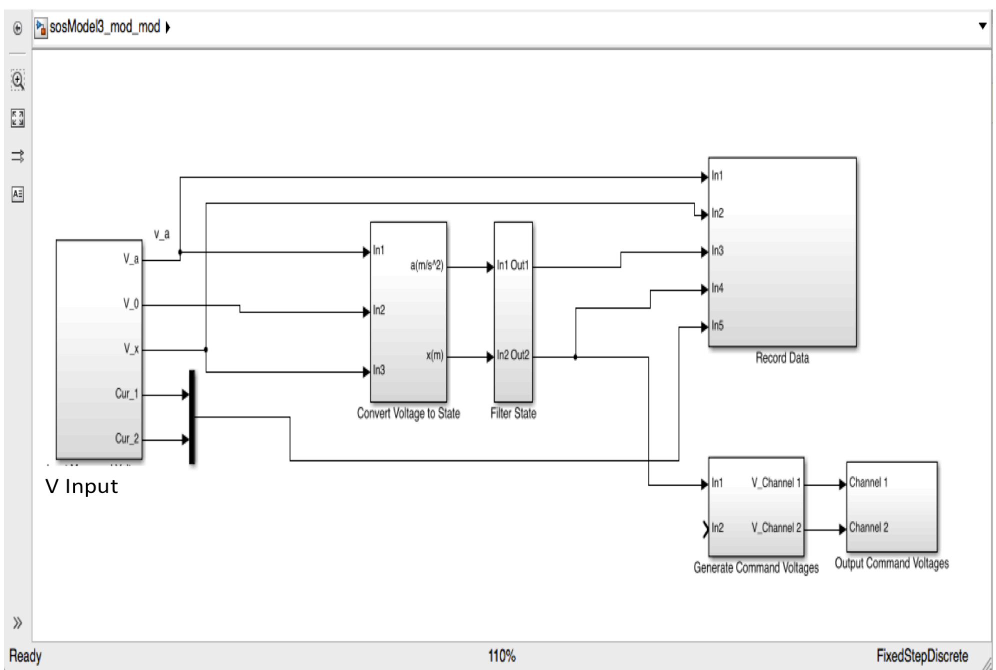

Figure 3: Simulink block diagram of control and data acquisition code running on the real-time OS

to capture and respond to all of the relevant dynamics. The loop first converts the voltage inputs to calibrated position and acceleration measurements. A dynamic Kalman filter from the DSP toolbox estimates the full state of the cart from the noisy sensor signals. A controller can then use the state estimate to inform the output voltage to the power supply and magnets.

C. Sensor Subsystem

The sensor subsystem comprises a Freescale Semiconductor MMA7361L accelerometer mounted to the cart and a Sharp GP2D120XJ00F IR position sensor. Due to its small size, the accelerometer can be mounted directly to the target cart without causing the payload to exceed specifications. However, the accelerometer cannot send its signal wirelessly because the necessary batteries and hardware would exceed the cart's weight payload. Extremely fine wire intended for medical applications provides power and data transfer while minimizing the effect on the cart's dynamics. Both sensors output analog voltage signals that are read by a NI 6861 PCIe DAQ card and converted from analog to a digital signal.

D. Actuator Subsystem

The actuator subsystem comprises three electromagnets and a two channel amplifier. The amplifier is a Carvin DCM 1500 audio amplifier. The amp accepts non-DC voltage signals on two channels and amplifies them, providing the currents pulled by the circuit up to current/voltage combinations, which exceed 1500 Watts between the two channels. {VERIFY THIS} The magnets are 15 mH laminate core speaker inductors. These parts are both off-the-shelf and designed to accommodate the large sinusoidal currents necessary to generate observable EC forces.

V. System Implementation and Assessment

The current implementation uses inexpensive, off-the-shelf to sense the state of the system with greater precision than any of the components could achieve on their own. A real-time OS provides high frequency sensing, data collection and either closed- or open-loop output.

A. Part Selection

A large part of the design phase was consumed by part selection because there is no standardized way to instrument a low-friction test bed. Each one is usually custom made for a specific purpose. One of the goals of this project has been to remedy this with a system that is replicable with easily available parts. The goal of an easily replicable system is so that labs and schools can avoid a long generic design phase and focus on the specifics of their own low-friction experiments. This section presents the considerations informing the ultimate part selection.

Accelerometers have high bandwidth, but estimate position poorly. Conversely, position sensors have poor bandwidth, but are able to measure position directly. Computer filtering can compose multiple sensors, allowing them to supplement each other. The choice in accelerometer was not critical because MEMS devices have become both cheap and high quality. However, there are many choices for linear position sensors – vision systems, optical encoders, laser sensors and infrared position sensors were all in consideration. These sensors all had a unique combination of price point, bandwidth, sensing range, sensing precision, and necessary computation. This test bed uses an IR position sensor because the sensor was inexpensive, precise, outputs easily convertible raw voltages rather than digital signals, and since the system doesn't require more than third of a meter sensing range the range of the sensor is not a downside.

There were several computing options available for reading analog voltage inputs, closing the loop, and producing analog voltage outputs. The three main possibilities were Labview, a microcontroller like an Arduino, and Simulink. The system required a high frequency control loop, which can only be achieved reliably with a microcontroller or a real-time operating system. Normal operating systems like windows reserve the right to put threads on hold, so it is not guaranteed that outputs happen exactly when they need to. Arduinos can run a control loop at high frequencies, but are limited both in on-board computing ability and the ability to record data. Labview works very well with all National Instruments products, but did not have the easy customizability this system required. Ultimately, Simulink xPC target offered the most benefits and the least downsides.

B. Sensor Verification

The following graphs show test data demonstrating the capabilities of the senor suite. Using an adaptive Kalman filter to estimate the true state of the cart, the system can achieve sub-centimeter position precision for system dynamics slower than 20 Hz. While not ideal, this is sufficient for eddy-current actuator tests, which have demonstrated maximum forces of 0.05 N. If these forces act on the target cart of mass 0.25 kg over a minimum sensing precision throw of 0.01 m (which is greater than the true minimum) the system dynamics will be on the order of 5 Hz – sufficiently slow for the sensor suite to measure.

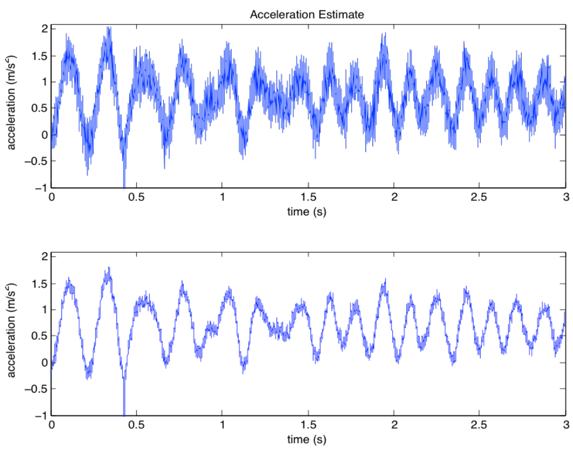

Figure 4: Acceleration estimate before (top) and after filtering (bottom)

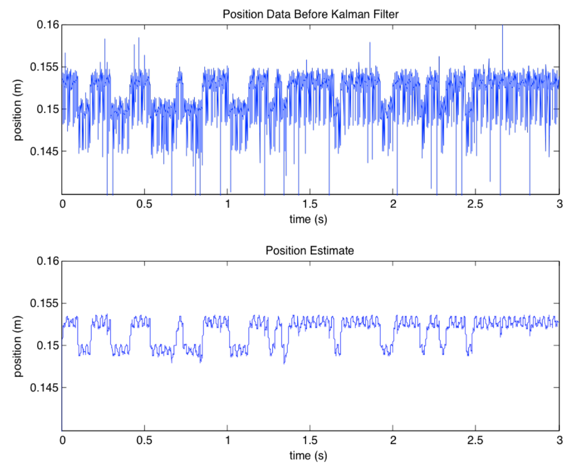

Figure 5: Position estimate before (top) and after filtering (bottom)

VI. Conclusion

The quest to design any new spacecraft actuator will eventually require experimental verification. There are several low-friction test bed models available for experiments requiring simulated microgravity dynamics. However, both planar air bearing tables and rotational test beds have downsides. They introduce unwanted dynamics, have states that are hard to measure, and are expensive partially because they require specialized parts as well as consumables. These downsides and the technological gap in contactless orbital interactions motivated the design of a new low-friction test bed. This 1-D test bed has several advantages: it is easy to replicate – built from off-the-shelf components; it avoids as many extraneous dynamics as possible; and it is extensible – the input sensors, output actuators, and components can easily be modified and replaced. As novel spacecraft construction becomes less specialized more widespread – the first satellite built by a high school recently achieved orbit – simple, inexpensive test beds will be increasingly important so that investigators can spend their time on the experiment itself rather than the experimental test bed.

Acknowledgements

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