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To rapidly and reliably acquire and maintain a laser on a long-distance, space-based target (or receiver), a pointing system capable of locking onto the position of a target (or receiver) over a wide field-of-view has been developed. The pointing/tracking system consists of a highly instrumented hexapod platform, a six-legged parallel kinematic machine capable of six degree-of-freedom (DOF) motion. This architecture is lightweight, highly fault tolerant, and capable of absorbing vibrations in all six DOF so off-axis vibrations do not induce on-axis errors through structural flexibilities. Accelerometers are used to measure ambient vibrations and reject them using an active control system. Optical sensors are used to measure pointing errors and reject them using decoupled, fault tolerant feedback control techniques. New models and control algorithms have been developed utilizing these measurements to provide tracking in a fault tolerant manner over a wide field-of-view. The control advances include: 1) Design criteria to maximize the hexapod's performance; 2) Decoupled control algorithms that result in high bandwidths for any rigid payload; 3) Optimal methods of reconfiguring the control following failures; 4) Methods for managing the overlapping capabilities of coarse and fine stages; 5) Adaptive algorithms to enhance rejection of monotone vibrations; and 6) Estimation algorithms to accurately identify the payload. Six DOF vibrations have been generated using a second hexapod, and robust force control algorithms have been employed to de-sensitize its control to payload structural dynamics.

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John E. McInroy and Jerry C. Hamann
February 5, 2002
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FOREWORD

To rapidly and reliably acquire and maintain a laser on a long-distance, space-based target (or receiver), a pointing system capable of locking onto the position of a target (or receiver) over a wide field-of-view has been developed.The pointing/tracking system consists of a highly instrumented hexapod platform, a six-legged parallel kinematic machine capable of six degree-of-freedom (DOF) motion. This architecture is lightweight, highly fault tolerant, and capable of absorbing vibrations in all six DOF so off-axis vibrations do not induce on-axis errors through structural flexibilities. Accelerometers are used to measure ambient vibrations and reject them using an active control system. Optical sensors are used to measure pointing errors and reject them using decoupled, fault tolerant feedback control techniques. The optical system consists of two staged sensors. For coarse, low bandwidth, passive measurements over a wide field-of-view (FOV), a camera system has been implemented. After initial acquisition, a fine, high bandwidth analog sensor (a Position Sensitive Detector, PSD) is employed for the control. New models and control algorithms have been developed utilizing these measurements to provide tracking in a fault tolerant manner over a wide field-of-view. The control advances include: 1) Design criteria to maximize the hexapod's performance; 2) Decoupled control algorithms that result in high bandwidths for any rigid payload; 3) Optimal methods of reconfiguring the control following failures; 4) Methods for managing the overlapping capabilities of coarse and fine stages; 5) Adaptive algorithms to enhance rejection of monotone vibrations; and 6) Estimation algorithms to accurately identify the payload.

To thoroughly test the pointing system, a test-bed must expose it to a large variety of six axis disturbance vibration profiles corresponding to different candidate applications. In addition, the test-bed should simultaneously slew the pointing system through relative motion profiles corresponding to the same applications. Because the pointing requirements are stringent, the disturbance requirements are equally stringent: a relative motion with 60 nano-radian accuracies must be created. Simultaneous precision relative motion and precision six axis vibrations cannot be achieved with commercially available platforms. However, a second hexapod platform (for disturbance generation) is ideally suited for this application: by reversing the vibration isolation functions, vibration generation capability is provided. The theory (modeling and control) necessary to make this modification has been developed. Special attention has been directed toward robust control, so that the disturbances can be generated for a wide variety of payloads, including those with resonant structural dynamics. This new, unexpected application of the hexapod platform demonstrates the versatility of the approach.

Contents

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1 Introduction and Problem Statement

This study developed new, fault tolerant solutions for future missions that require micro–precision vibration isolation and/or micro–precision pointing. All micro–precision applications share the need to reject noisy machinery disturbances. Figure 1 defines the micro–precision vibration isolation and pointing problems: (1) isolating vibrating machinery from a precision bus (location #1 in Figure 1) and (2) quieting and precisely pointing a payload attached to a noisy, coarsely pointed bus (location #2 in Figure 1).

Problem #1: 6-Axis	Problem #2: 6-Axis Micro-Manipulation
Vibration Isolation	and Platform Stabilization

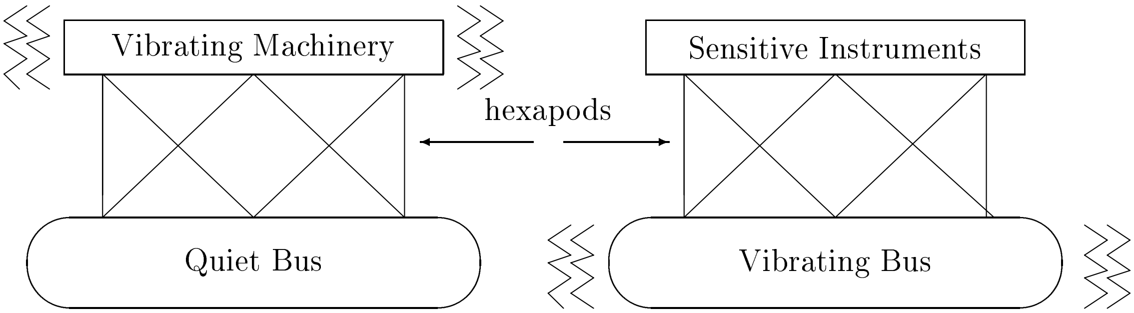

Figure 1: Problem #1: Vibrating machinery must be isolated from a precision bus (this is termed the *dirty box* problem because the machinery mounted on the hexapod "box" is mechanically "dirty", i.e. vibrating). Problem #2: A precision payload must be manipulated in the presence of base vibrations and/or exogenous forces (this is termed the *quiet box* problem).

In an earlier, funded ARO/BMDO DEPSCoR grant (DAAH04-96-1-0457), the University of Wyoming (UW) developed a novel 6-legged platform (or hexapod), ideally suited for these needs (see Figure 2). The new advantages this platform brings include combined pointing and isolation on a single device in six–dimensions, fault tolerance, and a rugged design. The earlier project developed the platform, along with controls which simultaneously perform both isolation and pointing. This study sought methods for enhancing the performance of the platform, especially concentrating on its ability to rapidly and reliably acquire and maintain a laser on a long-distance, space-based target (or receiver).

The pointing/tracking system consists of a highly instrumented version of the hexapod platform. This architecture is lightweight, highly fault tolerant, and capable of absorbing vibrations in all six DOF so off-axis vibrations do not induce on-axis

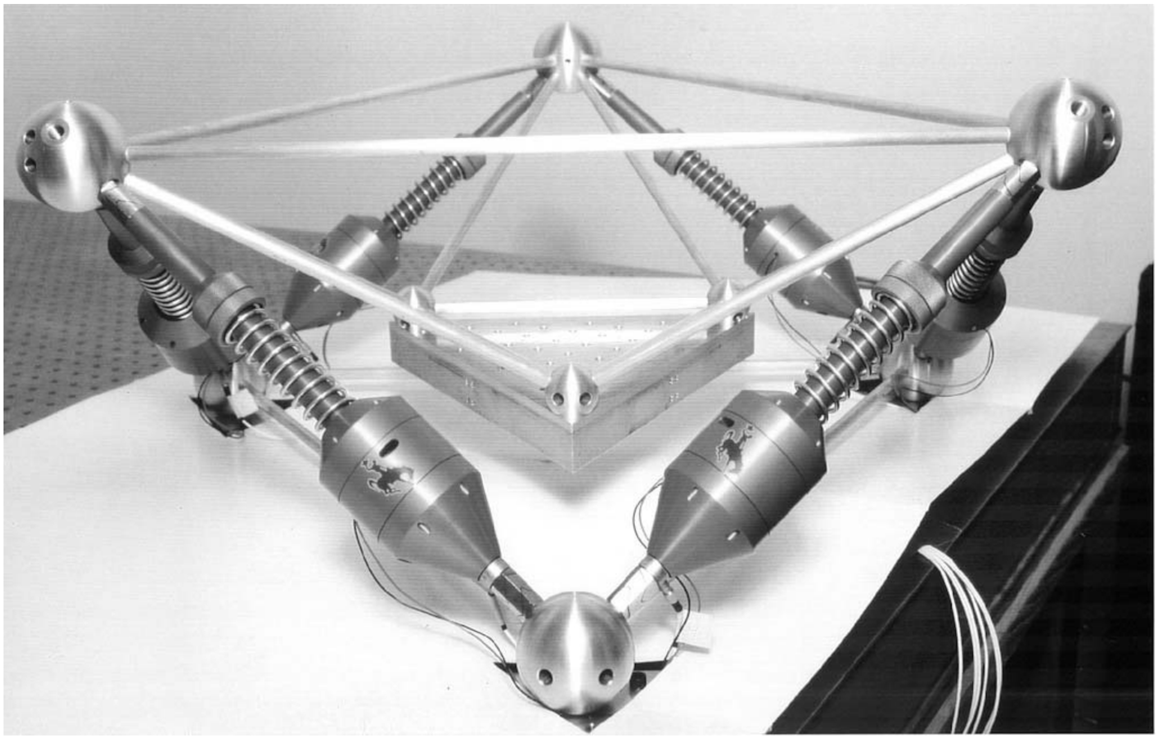

Figure 2: UW's flexure jointed hexapod. Voice coil actuators allow the lengths of each of the six smart struts to be slightly changed. By effectively "pulling its knees up," the system can be configured to address either of the problems presented in Figure 1.

errors through structural flexibilities. Accelerometers are used to measure ambient vibrations and reject them using an active control system. Optical sensors are used to measure pointing errors and reject them using decoupled, fault tolerant feedback control techniques. The optical system consists of two staged sensors. For coarse, low bandwidth, passive measurements over a wide field-of-view (FOV), a camera system has been implemented [16]. After initial acquisition, a fine, high bandwidth, analog sensor (a Position Sensitive Detector, PSD) is employed for the control. New models and control algorithms have been developed utilizing these measurements to provide tracking in a fault tolerant manner over a wide field-of-view. Methods for managing the overlapping pointing functions of the hexapod and a fast steering mirror have also been derived.

To thoroughly test the pointing system, a test-bed must expose it to a large variety of six axis disturbance vibration profiles corresponding to different candidate applications. In addition, the test-bed should simultaneously slew the pointing system through relative motion profiles corresponding to the same applications. Because the pointing requirements are stringent, the disturbance requirements are equally stringent-a relative motion with 60 nano-radian accuracies must be created. Simultaneous precision relative motion and precision six axis vibrations cannot be achieved

Figure 3: The top hexapod performs fault tolerant, high precision pointing and tracking. The lower hexapod induces high fidelity 6 axis vibrations matching candidate applications.

with commercially available platforms. However, a second hexapod platform is ideally suited for this application: by reversing the vibration isolation functions, vibration generation capability is provided. The theory (modeling and control) necessary to make this modification has been developed. Figure 3 depicts the resulting pointing and tracking hexapod on-board the disturbance generation hexapod. This new, unexpected application of the hexapod platform demonstrates the versatility of the approach.

High power laser weapons provide a striking example of the hexapod's utility in pointing and tracking applications. Most high power lasers bear some relationship to jet engines because flowing gases are combusted to produce light energy. This process generates significant unwanted vibrations. Although a hexapod may at first examination appear to be an exotic and complicated device, in some ways it is similar to the structural designs used for decades to mount aircraft engines. That is, six members are designed to carry predominantly axial loads so that the engine is rigidly constrained in all six degrees-of-freedom by a lightweight structure. The hexapod replaces the rigid axial members with active devices capable of absorbing vibrations and precisely pointing. Moreover, all the active devices are identical, thus lowering manufacturing and maintenance costs. This project has developed the technology necessary to incorporate within a hexapod structure the attributes of the most advanced pointing and tracking systems (including inertial stabilization, active pointing, and fault tolerance). This will allow the laser mount to consolidate several functions, with the resulting cost and weight advantages. Note that laser weapons are but one application of this very general pointing and tracking approach. For example, space-borne laser communication, where both a transmitter and active receiver are utilized, constitute an additional promising application area. In fact, any application requiring multi-axis vibration isolation and precision motion control may benefit. Examples include surveillance satellites, rotorcraft vibration isolation, micro-manufacturing, scanning probing microscopes, scanning electron microscopes, and semiconductor manufacturing equipment. All of these applications have a very wide positional dynamic range. In the case of laser weapons pointing, for example, rotations over tens of degrees are required, while maintaining accuracies down to millionths of a degree. This 10^7 dynamic range is typically achieved through several serial stages–often a coarse, fine, and perhaps a very-fine pointing system. Control methods that ensure these overlapping, multi-axis systems can accomplish both the required range of motion and bandwidth in a fault tolerant manner have been found.

Because the vibrational environment plays such a large role in any precision pointing and tracking system, it is important to test these systems with vibrations matching those expected. Since the hexapod can generate precise motion over a wide frequency range in all six directions, it is ideal for vibration generation. By creating a library of vibrational environments, many candidate applications can be quickly tested, resulting in savings of time and money. This will allow systems to be more thoroughly tested in the laboratory before commencing expensive field tests. If the payload is a lightweight structure, it will likely contain a number of resonant dynamic modes that can seriously degrade the capabilities of these vibration generators. Methods for de-sensitizing the generator to payload resonant dynamics have been found.

2 Summary of the Most Important Results

To rapidly and reliably acquire and maintain a laser on a long-distance, space-based target (or receiver), three main objectives have been pursued:

1. A pointing system capable of locking onto the position of a target (or receiver) over a wide field-of-view has been developed. The lock is maintained despite vibrations aboard the transmitting and receiving platforms, relative motion between the platforms, and some component failures. Vibrations in all six possible directions are absorbed, to prevent wear and cross coupling of vibrations through flexible structure dynamics. The system is lightweight and highly fault tolerant.

2. A test-bed capable of physically simulating space-based pointing and tracking systems has been established. Six degree-of-freedom vibrations analogous to those on-board a satellite have been induced. Relative motion between the platforms has been created. The vibrations match desired values for a wide range of possible payloads including those with resonant structural dynamics. Sensing time delays typical of the application in question are included.
3. The pointing/tracking system and test-bed have been combined to test operation under a variety of scenarios. Different distances, pointing accuracies, relative motions, etc. have been evaluated.

This section summarizes the progress made, beginning with the most fundamental advances that underpin all work and progressing to more advanced uses.

2.1 Design and Modeling of High Performance Pointing Platforms

In order to develop a high performance pointing and/or disturbance generation platform, the pertinent dynamics must first be fully understood. In addition, mechanical design criteria ensuring that the platform dynamics lend themselves to control must be known. The progress can be summarized as follows:

- A general dynamic model for flexure jointed hexapods has been derived.
    - Prior Stewart Platform models did not include the passive spring effects due to the flexure joints.
    - Base accelerations and exogenous payload forces are included.
    - The model has been experimentally verified.

Along the theoretical front, the dynamic model of flexure jointed hexapods was refined, and is now able to include base accelerations and exogenous payload generalized forces. Since these quantities are responsible for creating vibrations, their mathematical representation is essential for designing controls/structures which minimize the response to specific vibration profiles. Although exogenous payload forces have been included in prior hexapod dynamic models (for the non-flexure jointed case), base accelerations have not been included in any prior hexapod dynamic models in the literature. In order to achieve extremely precise motion which is free from nonlinear friction and backlash, the University of Wyoming (UW) hexapod utilizes flexures for all of its joints. Although these flexures eliminate friction and backlash, they do have an effect on the dynamics. The new dynamic formulation includes the effect of these flexures, and shows that, by proper design, the adverse effects of the flexures can be minimized. Dynamics that are especially easy to control can be designed by ensuring that the payload's center of mass is located at the hexapod's center. This restriction,

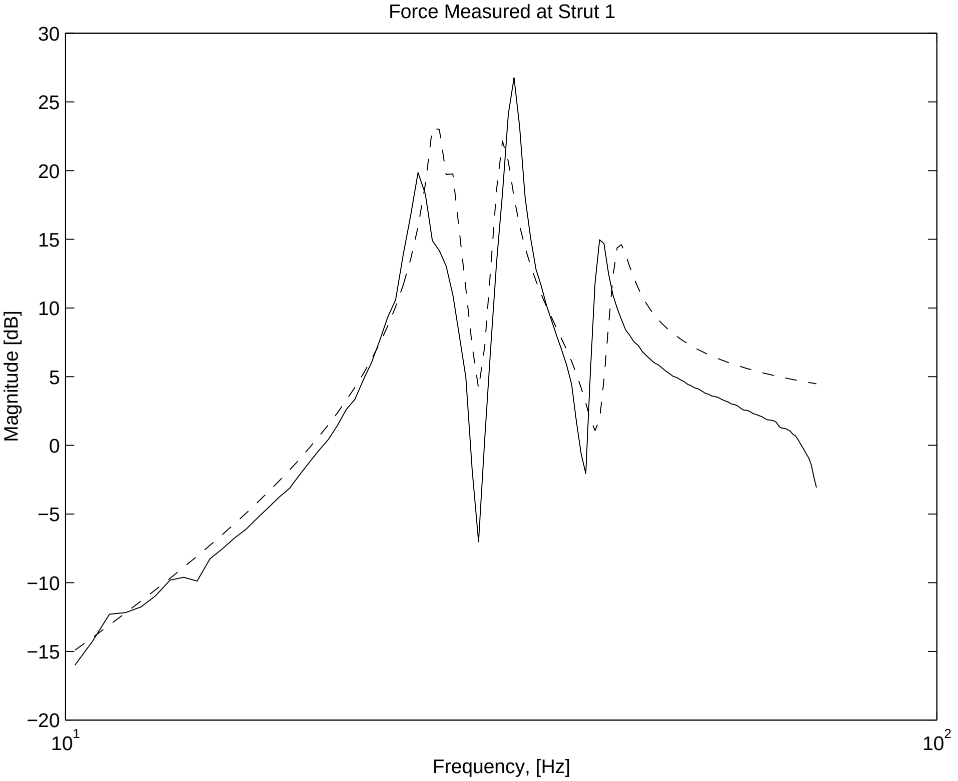

Figure 4: Modeled (dashed) vs. measured (solid) transfer function from the input of strut #1 to its force sensor output. All struts demonstrate a similarly close match.

however, is one that we've investigated thoroughly and learned how to overcome. Figure 4 compares the modeled response of a strut to its measured transfer functions. The basic concepts underlying most of these modeling and design advances were developed under the first DEPSCoR grant (DAAH04-96-1-0457). Final refinements and publication details were completed under this grant. Further details can be found in [1], [2].

2.2 Linear Control Improvements

The development of high accuracy pointing and tracking systems for space-based lasers presents a number of challenges. As a result of this research grant, several of these obstacles have been removed. In summary:

- Prior restrictions on the geometry of the payload have been removed, thus making it much easier to achieve high performance control.

- Optimal strategies for reconfiguring the control after a failure have been derived and experimentally verified.

- New methods for analyzing multi-axis systems with overlapping positional capabilities (e.g. coarse and fine stages) have been developed.

- To de-sensitize a hexapod based vibration generator from the payload and/or base resonant dynamics, force measurements have been used in a novel way.

2.2.1 Decoupled Control Algorithms Extended to Any Rigid Payload

By exploiting properties of the joint space mass-inertia matrix of flexure jointed hexapods, a new decoupling method has been derived and experimentally tested. The new decoupling method, through a static input-output mapping, transforms the highly coupled six input six output dynamics into six independent single-input single-output (SISO) channels. Controls for these SISO channels are far simpler than their multiple-input multiple-output (MIMO) counterparts; only six compensators are necessary, rather than the 36 compensators that would result from MIMO techniques. This enables high sample rate controls while facilitating advanced control features such as adaptation, fault tolerance, iterative learning, etc. Prior decoupling control methods imposed severe constraints on the allowable geometry, workspace, and payload. The new method loosens and removes these constraints, thus greatly expanding the applications. The experimental results indicate that the new approach is practical and improves performance. See Figures 5 and 6. For further details, see [4], [13], and [9].

2.2.2 Optimal, Fault Tolerant, Control Strategies

Improved methods for pointing the hexapod in a fault tolerant manner have also been developed. When less than six degrees-of-freedom (DOF's) are required (in precision pointing tasks, for example), the kinematic redundancy of a hexapod makes it possible to implement fault-tolerant algorithms. The DOF not used for pointing are termed Off Degrees-of-Freedom (ODOF's). When one or several of the platform legs fails, methods have been derived for finding a new, reconfigured control to maintain performance. Several new reconfiguration algorithms have been derived. First, a previous reconfiguration algorithm, based on choosing the same number of "off" degrees-of-freedom (ODOF's) as failed struts, is optimized by using the condition number, the maximum singular value, and the minimum singular value, respectively, as three criteria suitable for different applications. These three algorithms minimize joint space motions. To minimize normed Cartesian space motions, a least squares approach is developed. Experimental results indicate that this method yields superior performance, especially when the platform works at the edge of its workspace. Since only two legs are required to perform two-axis pointing, the hexapod can withstand up to four simultaneous failures of its legs. These failures must be of the "soft" type. During soft failures, the leg is immobilized, but still present (a third DEPSCoR grant has developed even more general techniques suitable for hard failures). The following

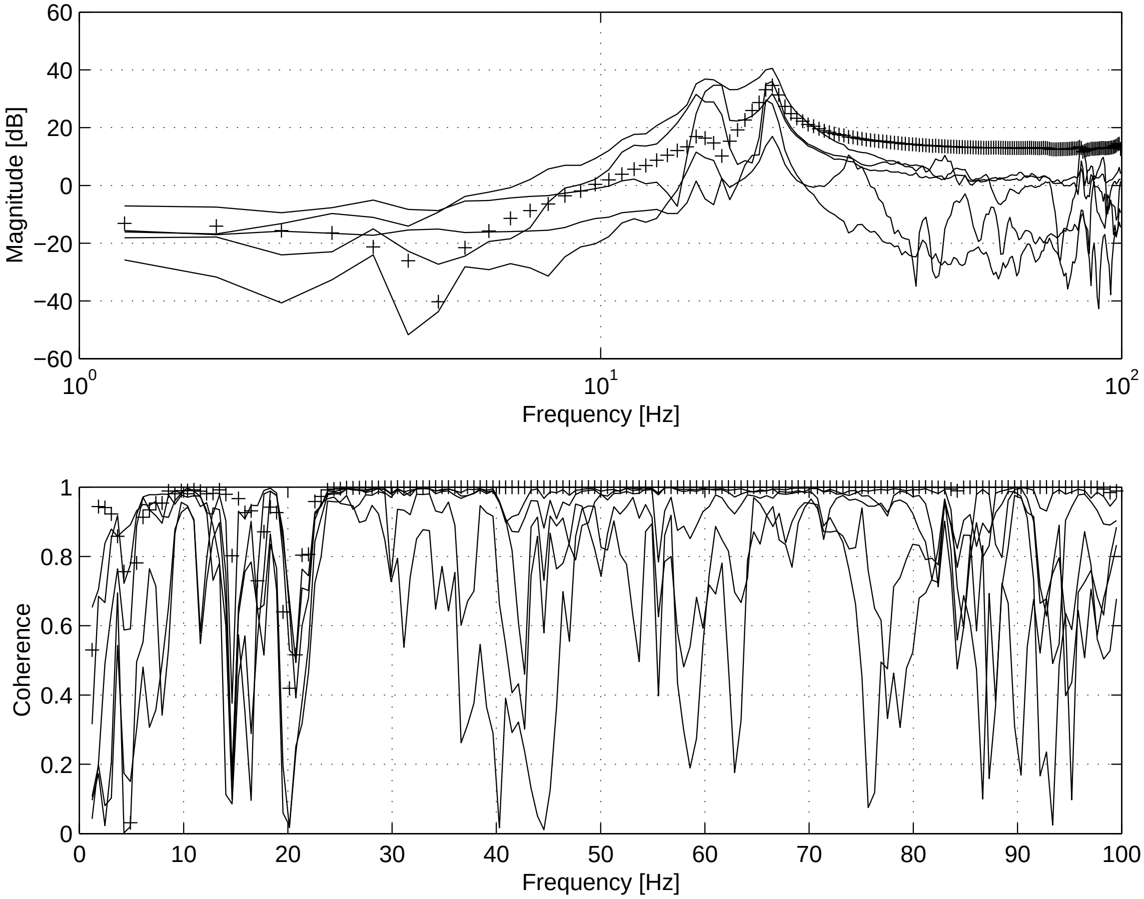

Figure 5: An earlier decoupling method doesn't work unless several restrictions are met. For example, the payload's center of mass was required to coincide with the hexapod's center. Since these requirements aren't met for this test, decoupling is not achieved, and the response that should be dominant (signified by "+" signs) is indistinguishable from responses in other directions.

figures illustrate the results when two legs have simultaneously failed, and different reconfiguration strategies are employed. Figures 7 and 8 illustrate that the reconfiguration can have a major impact on the motion and current ODOF's. Figure 2.2.2 illustrates the ability of the hexapod to track a spiral pattern (representative of those used for acquisition tasks) under four scenarios. The bottom plots show two different fault tolerant reconfigurations–both perform well, but the bottom right plot gives the best tracking accuracy. See [5], [6], [10], [14] for further details.

2.2.3 Overlapping Controls for Fast/Slow and Coarse/Fine Stages

When a number of different actuators are connected together by complex kinematics, it is not obvious if (and how) the combined system can achieve both position and

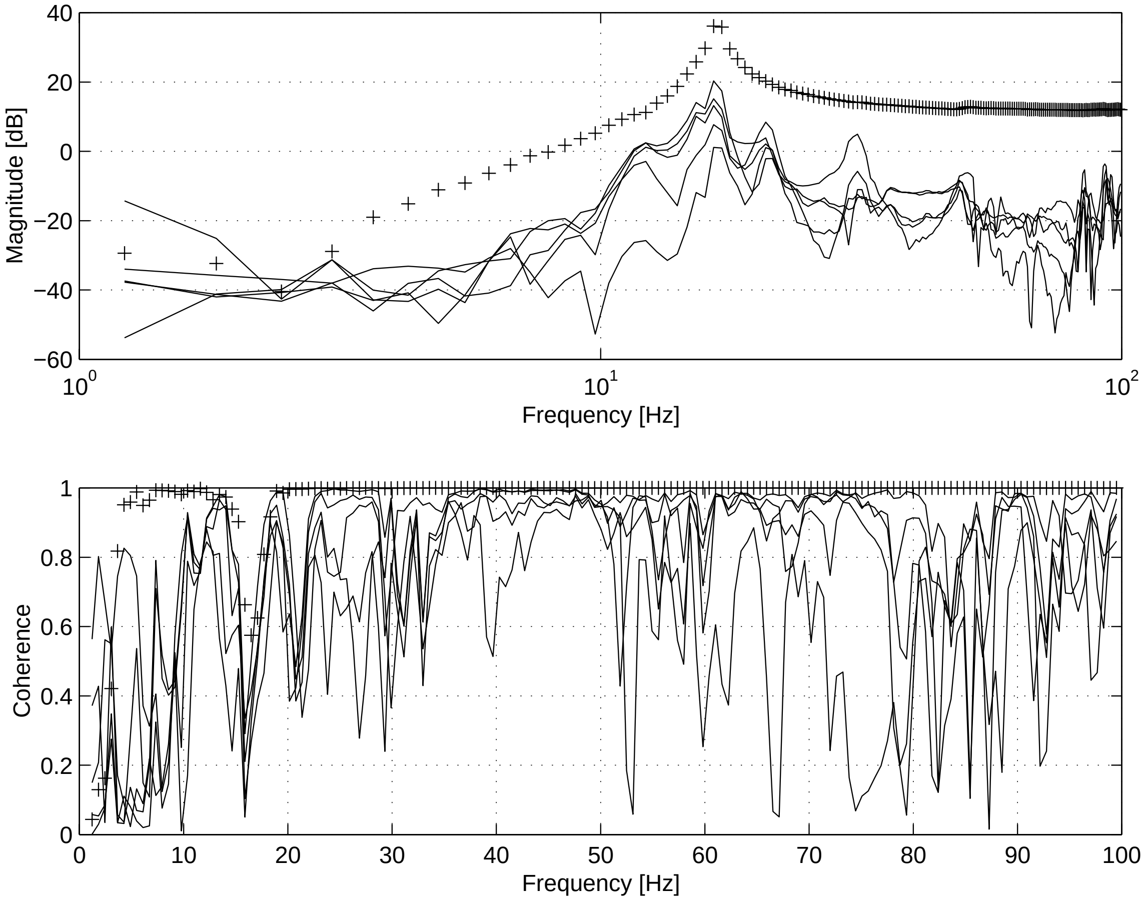

Figure 6: Using the new decoupling method under identical experimental conditions produces a response clearly dominated by the desired axis (the decoupled axis is denoted by "+" signs).

velocity goals in several axes. For instance, parallel *linear* actuators are often used to produce *rotational* motion because the parallel configuration provides high stiffness to weight, fault tolerance, etc. Both hexapods and commercial fast steering mirrors utilize this strategy, among others. To realize a fine and very-fine stage in a fault tolerant manner, both a hexapod and a fast steering mirror have been connected in series. General methods for analyzing the positional and velocity capabilities for these kinds of systems have been found. They are especially important for reconfiguring the system when failures occur. Figure 10 depicts a commercial fast steering mirror mounted on the hexapod, while [11] develops the analytic theory.

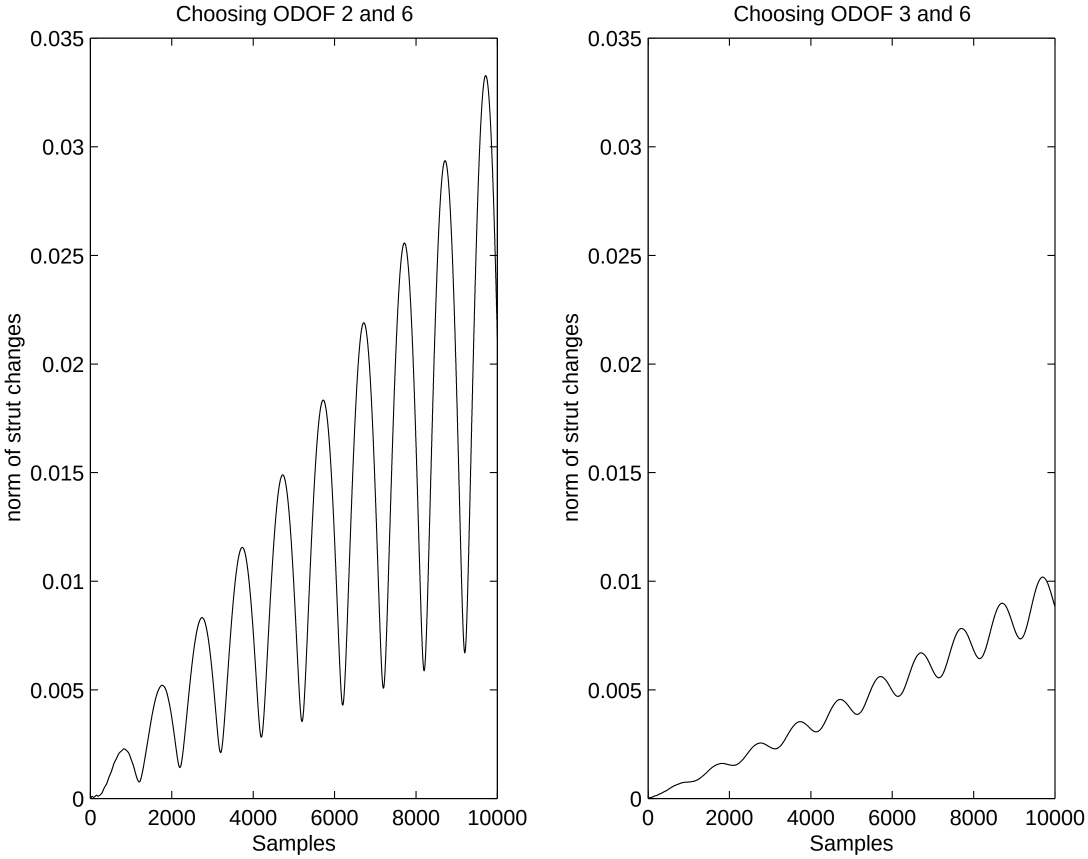

Figure 7: Comparison of strut movements under different choices of ODOF's

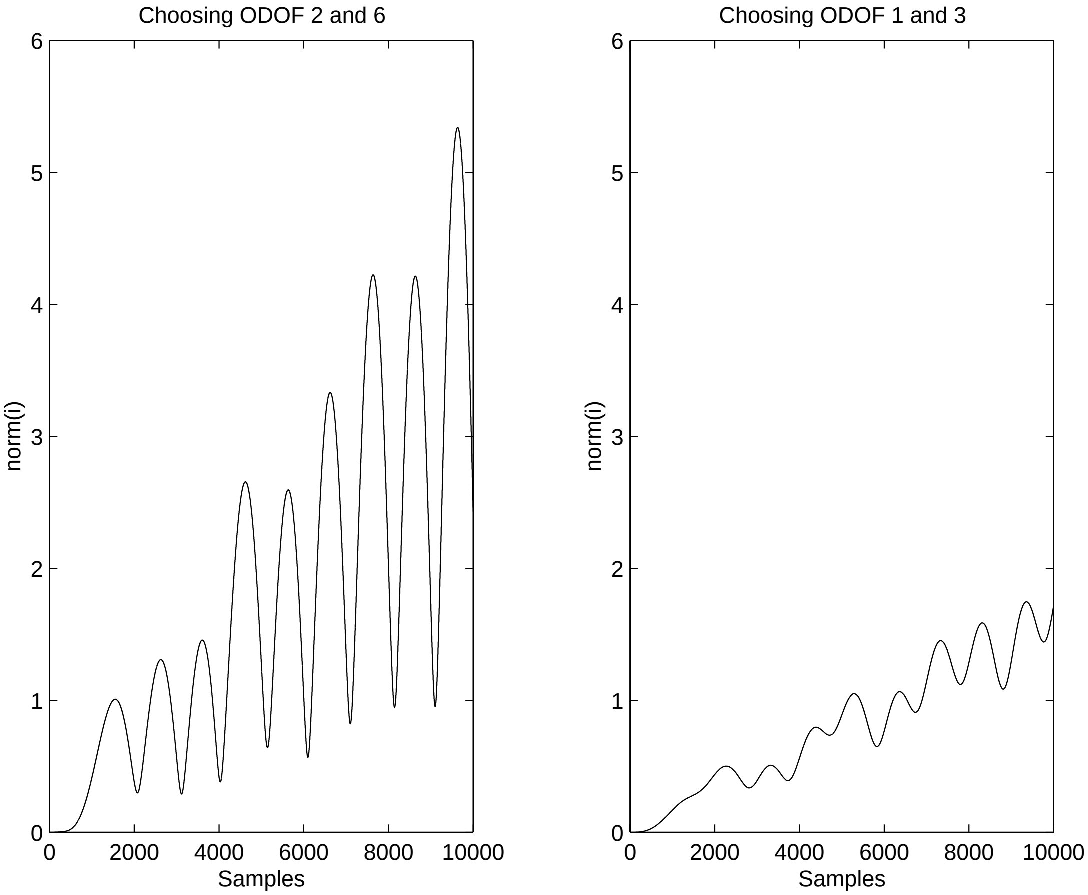

Figure 8: Comparison of required current under different choices of ODOF's. Norm($\dot{l}$) signifies the norm of the strut length changes.

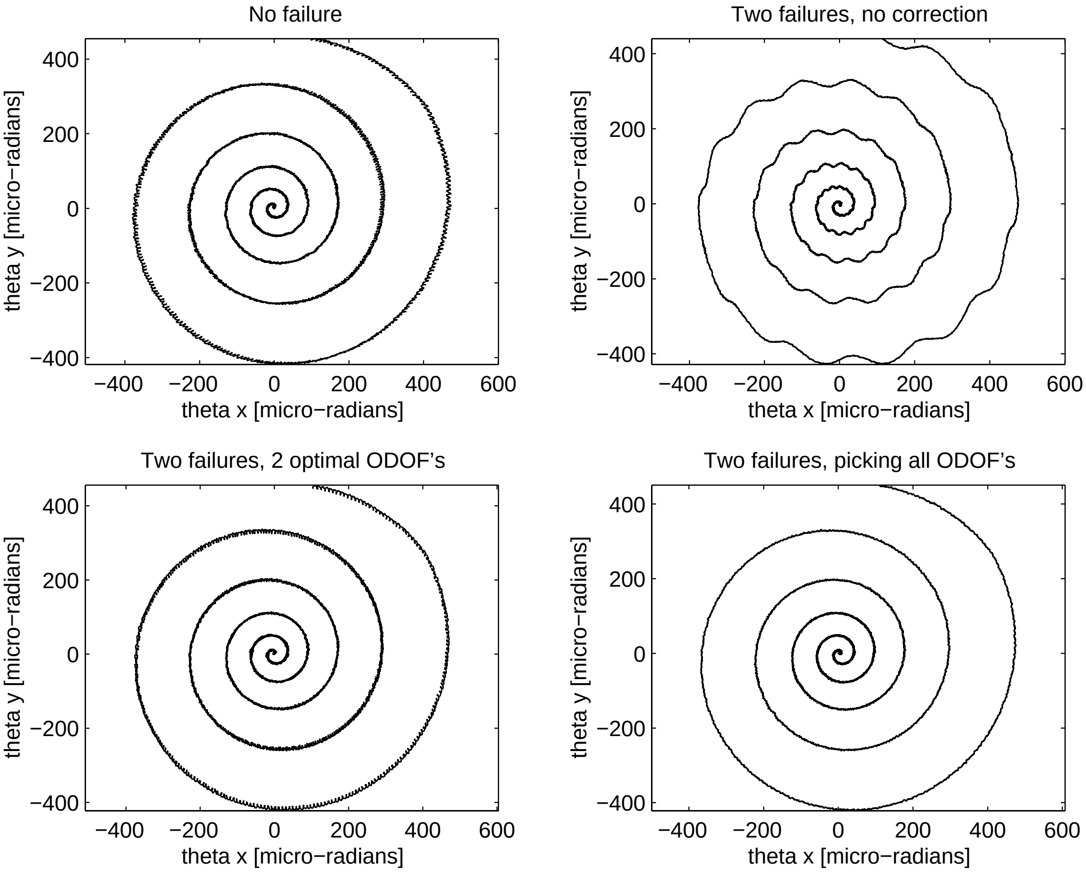

Figure 9: Tracking spirals with and without correction

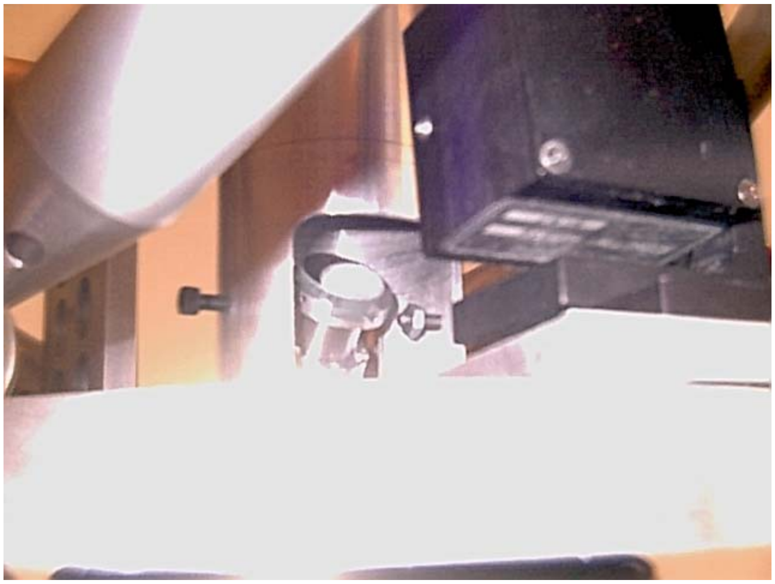

Figure 10: A commercial fast steering mirror (PZT based) is mounted on top of the hexapod's payload plate.

2.2.4 Force Feedback to Decrease the Sensitivity to Base and Payload Resonant Dynamics

Generating vibrations that accurately match those expected during operation is a vital element of testing. However, the resonant dynamics present in many lightweight truss structure payloads can seriously limit how accurately vibrations are applied to the payload. To de-sensitize the vibration generator from the payload dynamics, force measurements have been used in a novel way.

With minor modifications, the same algorithm used to de-sensitize a vibration *generation* control system from resonant *payload* dynamics can be utilized to de-sensitize a vibration *isolation* control system from resonant *base* dynamics. Because many vibration isolators are mounted on lightweight aircraft or spacecraft, the new algorithm will improve vibration isolation. In some applications, both the base and payload contain resonant dynamics. A modified version of the force control algorithm is simultaneously insensitive to both of these dynamic uncertainities. See [15] for more details.

2.3 Adaptive Sinusoidal Disturbance Cancellation for Precise Pointing

While wide-band rejection of vibrations is always of interest, many applications contain vibrations that are dominated by a single frequency. For example, a helicopter's rotor typically produces strong vibrations near about 11 Hz. Cyrogenic pumps usually

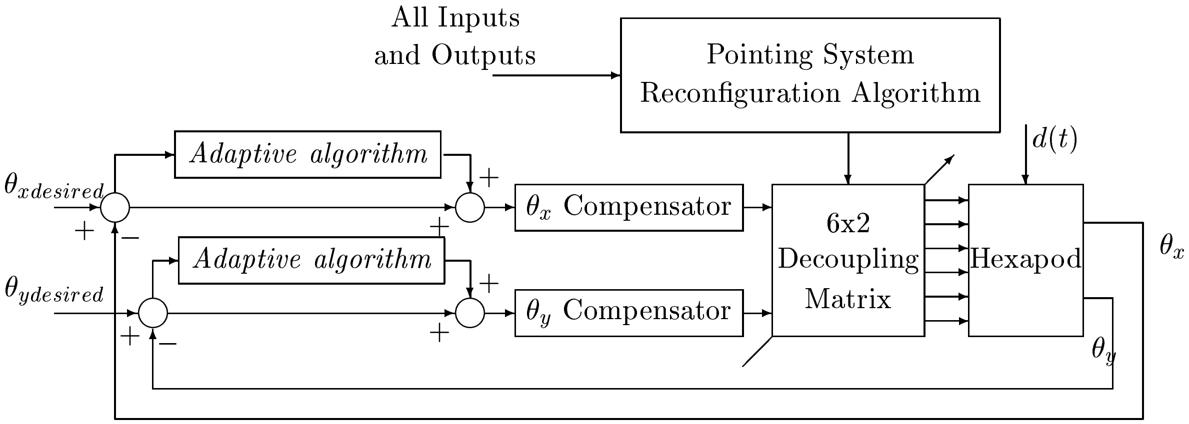

Figure 11: Strategy that combines adaptive sinusoidal disturbance cancellation with linear pointing control.

operate at a single rate, thus the vibrations caused by them are monotone, reaction wheels have a nominal speed of rotation, etc. To maximize rejection of these types of vibrations, an algorithm which combines an adaptive sinusoidal disturbance cancellation scheme with fault tolerant pointing algorithms for hexapods has been derived. This results in a fault tolerant pointing system capable of low frequency tracking, mid-frequency rejection of large monotone disturbances, and high frequency passive vibration isolation. Since often the frequency of the monotone sinusoidal disturbance cannot be precisely known, a Phase Locked Loop (PLL) algorithm is used to capture the frequency, and a method for PLL design has been developed. The decoupled pointing approach developed under the DEPSCoR grant (DAAH04-96-1-0457) has been augmented with an adaptive algorithm (shown in italics, Figure 11). Experimental results on the University of Wyoming platform demonstrate that pointing errors caused by a monotone disturbance decrease 50-fold even in the presence of multiple actuator failures (Figure 12). Further details can be found in [7], [12], and [17].

2.4 Estimation of Payload Mass/Inertia Matrices

In order to obtain the highest performance possible, the payload's dynamics must be known as accurately as possible. For instance, the decoupling algorithm discussed earlier [4] requires the payload's mass/inertia matrix. Using measurements of acceleration and force, the problem becomes solving an over-determined set of linear equations $\mathbf{AX} \approx \mathbf{B}$ with the constraint that the matrix $\mathbf{X}$ be symmetric and positive definite. This identical problem arises in a number of contexts, including estimation of robot dynamics, covariance, and smart structure mass and stiffness matrices. In

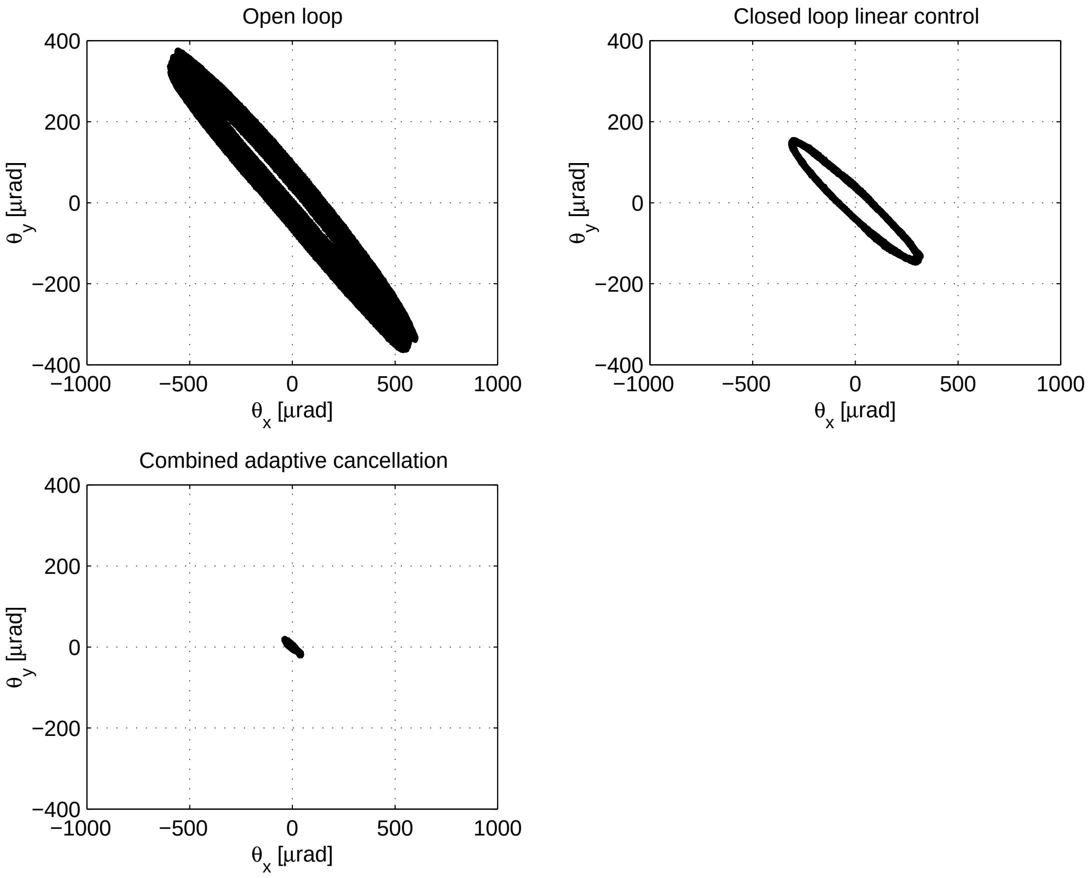

Figure 12: Plots of pointing error θ_x vs θ_y.

the classical least squares method the measurements of $\mathbf{A}$ are assumed to be free of error, hence, all errors are confined to $\mathbf{B}$. Thus, the "optimal" solution is given by minimizing the optimization criterion $\|\mathbf{AX} - \mathbf{B}\|_F^2$. However, this assumption is often impractical. Sampling errors, modeling errors, and, sometimes, human errors bring inaccuracies to $\mathbf{A}$ as well. For the hexapod's payload, both $\mathbf{A}$ and $\mathbf{B}$ contain errors because they contain actual (and therefore noise contaminated) measurements of force and acceleration. To include these effects, a new optimization criterion is introduced, based on area, which takes the errors in both $\mathbf{A}$ and $\mathbf{B}$ into consideration. Under the condition that the data matrices $\mathbf{A}$ and $\mathbf{B}$ are full rank, which in practice is easy to satisfy, the analytic expression of the global optimizer is derived. A method to handle the case that $\mathbf{A}$ is full rank and $\mathbf{B}$ loses rank is also developed. Figure 13 illustrates the estimation errors for the 21 independent parameters of the payload's mass/inertia 6×6 matrix. This has improved decoupling and therefore increased the control gain. The new (SPDE) method significantly outperforms the standard (LS=least squares) technique. See [3], [8] and [18] for further details.

2.5 Conclusions

As a result of this study, the following conclusions have been reached: Flexure jointed hexapods have unique abilities to stabilize and point a platform in many directions over a very broad range of frequencies in a fault tolerant manner. Methods of designing the hexapod to simplify its control have been found. Using these methods, decoupled, optimally fault tolerant controls have been derived and tested experimentally. These controls can be further enhanced by an adaptive control algorithm which provides high rejection of monotone vibrations.

It is our opinion that this technology will prove to be very valuable for a variety of both military and commercial needs.

3 List of Publications

The reference section offers a complete list of the publications resulting from this project. The papers are organized as follows: (a) Papers 1-3 are published in peer-reviewed journals; (b) Papers 4-8 are published in non-peer-reviewed journals or in conference proceedings; (c) There are no papers presented at meetings, but not published in conference proceedings; (d) Papers 9-12 are manuscripts submitted, but not published; and (e) Papers 13-18 are M.S. and Ph.D. theses resulting from the grant.

4 Inventions

None.

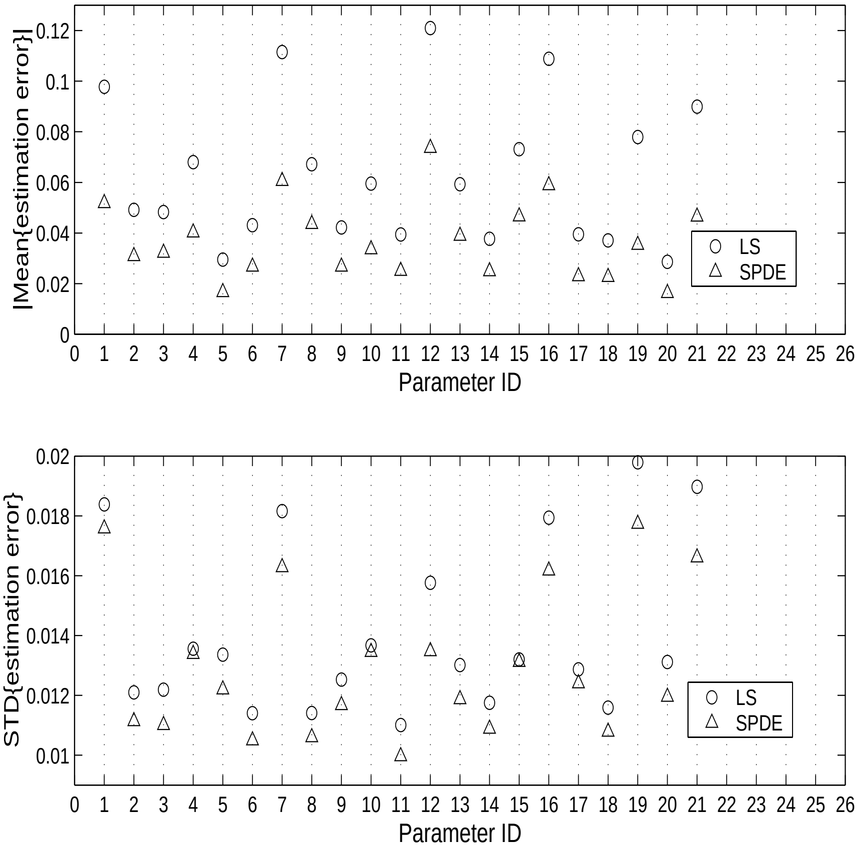

Figure 13: Comparison of the LS and the SPDE methods: absolute mean and standard deviation of the estimation errors. Mean{} and STD{} stand for the mean and the standard deviation, respectively.

5 Scientific Personnel Supported by this Project

Dr. John McInroy (faculty), Dr. Jerry Hamann (faculty), Dr. David Walrath (faculty), Dr. Xiaochun Li (PhD 2000), Dr. Yixin Chen (MS 1999, PhD 2001), Haomin Lin (MS 2000, PhD in progress), Yong Yi (MS 2001, PhD in progress), Ning Zhou (PhD in progress), Uditha Piyasena (M.S. 2000), Jing Ren (PhD graduate student), Linsong Wang (PhD graduate student), Zhisong Wang (PhD graduate student).

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