The experimental program in support of stiff-suspension active seismic isolation for LIGO-II

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1 Introduction

This document is provided in response to a request for documentation made by the ad-hoc "Technical Advisory Group," convened by the LSC and the LIGO Laboratory to technically evaluate various proposed seismic isolation (SEI) conceptual designs for LIGO-II. Specifically, this report responds to the Feb. 4, 2000 email request for "A Prototype Test Program Plan." As requested, this report will only cover the elements of our experimental program that will likely lead to results usable to the committee by April, 2000.

We have identified some aspects of our design's performance that we believe are crutial to meeting the requirements[1]; these represent risk to our approach if not well understood. Some understanding can be gained through modeling; our modeling program is described in a companion document, "Computer modeling and simulation in support of stiff-suspension active seismic isolation for LIGO-II," by Lantz, et. al. Here we describe the things best understood through expermental tests, and our polans to carry out these tests.

1.1 Brief overview of stiff active conceptual design

Since this document preceeds the requested "Baseline LIGO-II Implementation Design Description," a brief description of the elements of our cononceptual design is needed to establish a vocabulary for further discussion.

LIGO-II's test mass suspension system is being developed by the GEO group at the University of Glasgow[2]. The interface between it and SEI as well as the performance requirements on SEI are set out in [1]. A well-defined interface has been chosen in order to allow independant testing of the two detector components, and to facilitate their separate parallel development efforts in different continents.

The BSC geometry requires SEI to support its payload from above and the HAM geometry requires payload support from below. This will require two different versions of our SEI design. However, every effort is being made to confine the differences to the physical

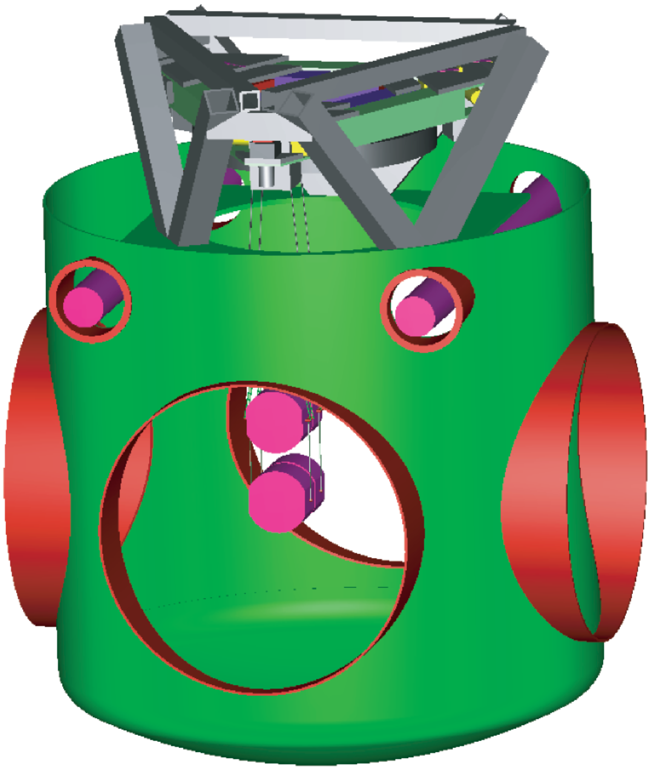

Figure 1: Drawing of the proposed design (here rendered in the BSC configuration.) A single-layer active seismic isolation platform supports the quadruple pendulum test mass suspension.

mounting structures that connect to the optics table and to the support tubes (which enter the vacuum system.) For this reason, we expect that the performance of the two systems will be similar, and the implementation challenges will be similar, so in this document we will not generally differentiate between the two versions.

Our overall design consists of a hydraulic actuator external to the vacuum system and a two-stage active siesmic isolation platform inside the vacuum.

1.1.1 External hydraulic actuator

The physical SEI/SUS interface consists of an optics table from which the SUS will be hung (for optics in BSC chambers), or on which the SUS cage will rest (for optics in HAM chambers). SEI is responsible for this optics table. For periodic manual alignment, SEI must be able to adjust the table's position and angle to allow the full range of the bellows (±5 mm).

At frequencies below the measurement band of LIGO, there are large amplitude disturbances which can easily be attenuated outside the vacuum chamber. These are the micro-seismic peak at 0.17 Hz, diurnal tidal changes and thermal / seasonal drifts that approach zero frequency (DC). For these disturbances, an actuator is needed that is capable of maintaining large ($\approx .5$ mm) DC offsets. Zero frequency pointing is typically addressed mechanically, but in this case, attenuating the microseismic peak requires low noise performance that is difficult to attain with hard-mount (gear driven, contact) mechanical systems. The solution currently under investigation is the use of quiet hydraulics, shown in Fig. 2.

The design specifications of the quiet hydraulic actuator are: ±1.0 mm of throw, 2 Hz upper unity gain frequency, and working fluid pressure of 75 psi. (The rare adjustments > 1.0 mm are accomplished with screw ajustments in series with the bellows mounting.) The large throw of the actuator is easily sufficient to compensate for tidal and microseismic motion at the LIGO sites, and we expect that the ISC designers will choose to apply that global signal here. The pump power requirements remain modest by virtue of the relatively low upper unity gain point at 2 Hz. While the bandwidth of the system could be increased with a more powerful source, isolation at higher frequencies is better addressed inside the vacuum chamber.

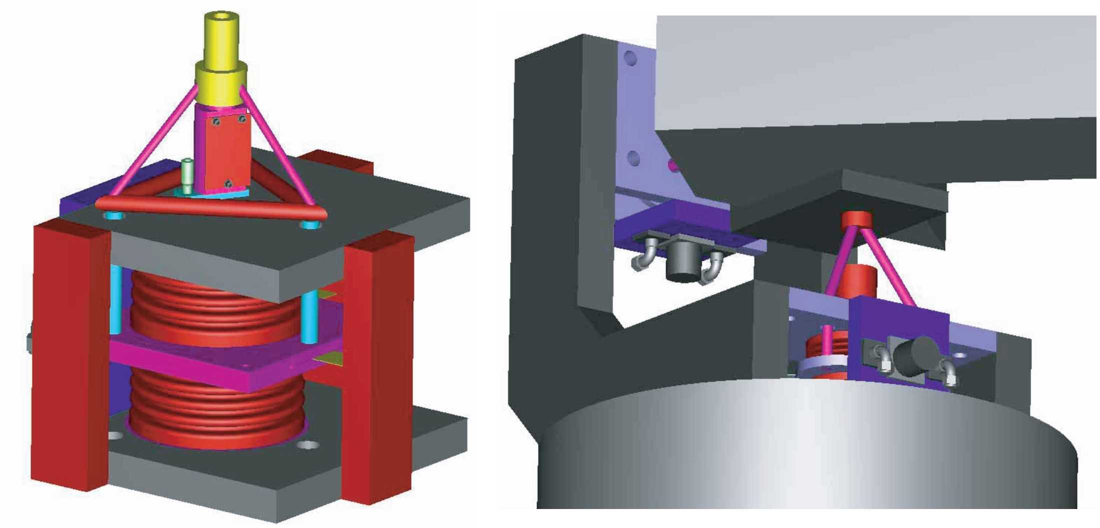

Figure 2: At left is a 1-DOF quiet hydraulic actuator. The gray blocks and red pillars form the reaction frame and are fixed in place. The two red bellows are pumped differentially to move the center purple actuation plate. The yellow bolt at the top attaches to the payload, and the actuation plate is attached to the payload by the rod assembly. An optical sensor (red and magenta) is placed between the yellow actuation point and the frame to allow low frequency servo stabilization. At right, two are shown in the 2-DOF configuration as would be employed in LIGO-II.

1.1.2 Two-stage active siesmic isolation platform

The in-vacuum system, shown in the BSC configuration in Figure 1 is a cascaded two-stage active isolation platform. The stages are suspended through stiff blade springs and short pendulum links, giving natural frequencies in the 2 - 4 Hz range. The inner plaform stage is built around a 1.5 m diameter optics table (BSC) or a larger rectangular table (HAM). For each suspended optic, the SUS is mounted on this flat table, and may be positioned and oriented as desired.

Global control signals for both optic position and angle may be distributed to each of the three components, large slow motions to the hydraulic outer system and progressively faster and smaller ones to the inner layers, ultimately to the test mass.

Local damping and noise-reduction control signals are generated for each DOF in the in-vacuum active platform by a combination of short- and long-period seismometers and position These sensors will need to be encapsulated in small chambers filled with trace gas, complete with electrical feedthroughs. The actuators are electromagnetic non-contacting forcers. These apply forces between adjacent stages. Both the SEI and SUS systems benefit from all DOFs being exposed to active damping in that they can recover well from accidental excitation.

The SEI component of the BSC scheme very much resembles the pre-prototype built and tested at JILA over the past decade The JILA development effort was directed towards a much more ambitious goal (to detect GWs at 1 Hz), so our scheme can benefit from the JILA experience and 3-D modelling effort without the need for the ultra-high-performance seismometers that were part of JILA's development work. Instead, we can use commercial, off-the-shelf seismometers, greatly simplifying the scheme and reducing risk. The choice of stiffer suspension also promises better thermal drift performance. The prototype tests should show if these changes from the JILA demonstration help.

2 Experimental Activities

Several experimental tests and simulation tasks are desirable in order to gain confidence that we can meet the requirements. These will be highlighted as the prototype tests are described.

2.1 Quiet hydraulics test

To demonstrate quiet hydraulics in alignment and low-frequency isolation, we have designed an actuator and test fixture which are currently under construction. The test fixture is designed to support two actuators in a condition that is similar to the final implementation in LIGO II. In this environment, we will characterize the noise, servo behavior, and dynamic range of the actuators. This testing will begin in March and continue for the following three months. We will characterize the noise performance by April.

The test fixture (Figure 3) is designed to test the actuator in a manner that is representative of the final application supporting one corner of a LIGO in-vacuum SEI. Two actuators are arranged orthogonally about a 300 kg. mass. Each actuator is collocated with a long-period seismometer and a position sensor. Two additional seismometers are placed on the ground next to the suspended mass for feed-forward control and to relative sensor

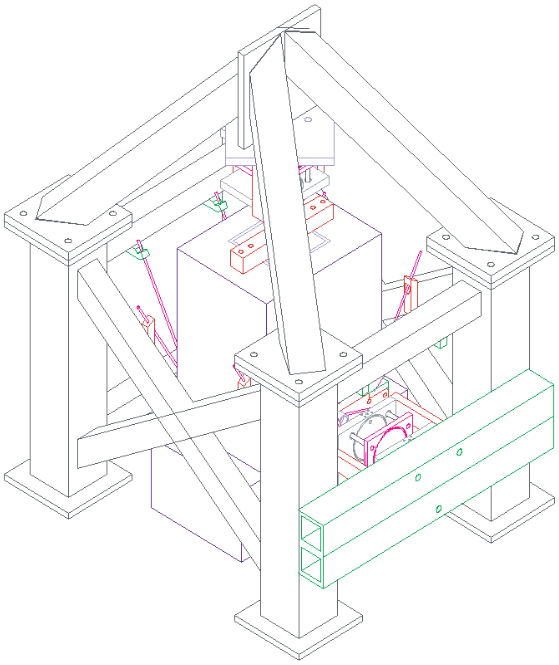

Figure 3: Design for the hydraulic actuator test fixture. The blue block in the center is the 300kg test mass, which is supported by eight large off-load springs (in magenta). The steel frame (gray) holds the off-load springs and two hydraulic actuators, one on the side and one on the top. The seismometers are imbedded in special holders within the blue test mass.

correction. The large support frame and suspended mass enable us to apply significant forces and measure any resulting noise.

2.2 Two-stage prototype

The principal goal of the Two-stage prototype is to demonstrate the performance and robustness of a two-stage active isolation system, similar in design and construction to the analogous active stages of the reference design proposed to meet the LIGO-II seismic isolation requirements. A drawing is shown in Figure 4. The prototype has been designed to fit in the Nu-Vac vacuum chamber at MIT (in the same high bay as LASTI). That chamber includes a heavy aluminum table which stands on legs penetrating the vacuum vessel through belows to the floor. The table is being modified for attachment of the external support structure. The structural members shown have been designed and FE modeled using 3D CAD software, and are currently in production by JILA and its contractors. We expect to keep a current version of the production status on our web site.

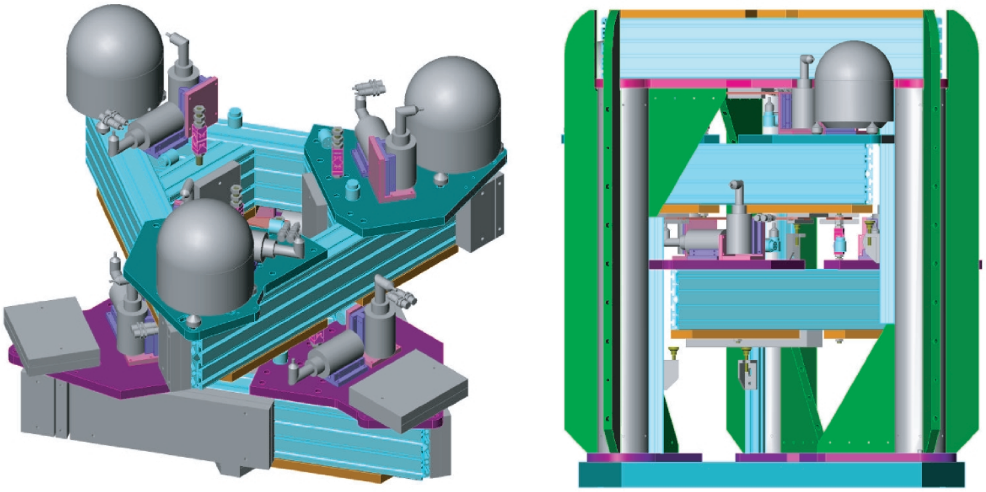

Figure 4: Drawing of the two-layer active seismic isolation platform under construction at JILA and to be installed in a vacuum system at MIT. The width of the platform stages is approximately 1 m.

2.2.1 Vibration attentuation test

The performance demonstration is intended to show a ground-to-payload vibration transfer function equal to that required of the two active stages in the reference design. In particular, demonstrating adequate performance in the 0.1-1 Hz range is a key goal. This will be an isolation transfer function measured with the ambient input noise at MIT, and therefore will not necessarily demonstrate the system noise performance required at a LIGO site. However, this latter performance may be demonstrated if time and conditions permit, either with feed-forward techniques or during quiet times.

Broadly defined, “similar in design and construction to the active stages of the reference design” means that the portion of the dynamic model describing the two active stages in the reference design can be used to model the rapid prototype with minimal change in parameters. In short, the Two-stage prototype will validate the control system dynamics model of the reference design, the sensors, the forcers, the control topology and the control laws. The prototype will also validate some mechanical design choices (e.g., triangular platforms, instrument pods), mechanical components (e.g., springs, flexures) and procedures (e.g., assembly, alignment, operation). This similarity is further defined in Two Stage Prototype Concept below.

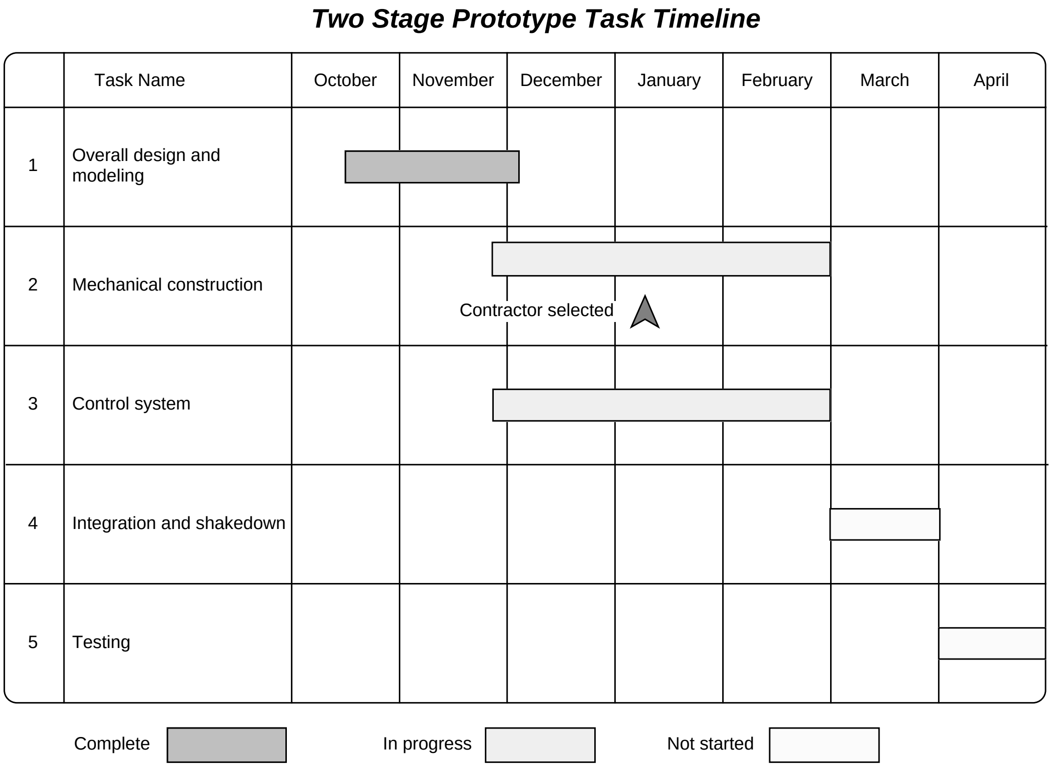

Figure 5: Task timeline for the two-layer active prototype.

2.2.2 Robustness test

The robust operation of two cascaded stages is also a goal, and is to be demonstrated by operation at the required isolation performance level for a substantial period at a high level of availability. Many feel that this sort of robustness can only be convincingly shown in a physical demonstration and not by use of computer models.

This prototype demonstration will also show how dispersed members of our team can marshal the resources and exercise the project management to design, fabricate, integrate and shake down an isolation system appropriate to LIGO-II. The prototype will also familiarize us with fabricators and materials and component suppliers.

The Two Stage Prototype will demonstrate the performance required by the LIGO II with similar, but not identical components. For this reason, it has some features, such as control system components and topology, which closely mimic our reference design for a LIGO II SEI and others, such as the structural foundation, which do not. We have tried to mimic the LIGO II situation wherever critical to demonstrating our system's performance. So, for example, we have not attempted to meet the vacuum requirements or mimic the payload dynamics for lack of time and definition, respectively. We don't expect the former present a problem, and the latter is being tested at Stanford. We expect other tests may follow to address the vacuum and other interface requirements, leading eventually to a full-scale prototype test at LASTI.

The most important feature of this prototype is that the two active stages will have all of the control system elements (i.e., sensors, actuators, controllers) in the two active stages of the reference design, in the same topology. Control signals originating outside the two active stages in the reference design (e.g., global length control, stage #0, payload signals) will not be present, except possibly by simulation.

2.2.3 Plans and schedule

The top level tasks in our Work Breakdown Structure follow. Some of these have been completed. The top-level schedule is shown in Figure 5.

- Task 1, Overall design and modeling
  - Define goals and concept
  - Identify subsystems: number of platforms, control loops, sensors
  - Specify major performance parameters: uncoupled frequencies, isolation per stage, sensor noise, rms motion
  - Specify structural and control requirements: scale, structural resonances, gain per stage, sensor and actuator requirements
  - Set Two Stage Prototype orporate operational requirements: fabrication, assembly, alignment, vacuum preparation, installation, adjustment
  - Model performance
  - Model "error effects"
- Task 2, Mechanical construction
  - Identify and initiate procurements which are clear or require long lead time Convert conceptual design to engineering design
  - Identify and select contractor
  - Begin vacuum system preparations
  - Contractor fabricates major structural components: space frame/cylinder, stages Inhouse shop fabricates small components: brackets, pods, vacuum enclosures for sensors
  - Test assembly for fit
  - Ship from JILA to test site (MIT)
- Task 3, Control system
  - Identify and initiate procurements which are clear or require long lead time: forcers, sensors, digital controller

  - Specify electrical connections for vacuum system
  - Fabricate feedthroughs for vacuum system
  - Refine control design: detailed block diagram, compensation, acquisition, Setup controller, make operational, make tests with sensors and forcers
  - Generate and test operating code

- Task 4, Integration and shakedown
  - Conduct early test of vacuum enclosure for sensors and actuators
  - Ship parts to test site
  - Prepare for vacuum
  - Assemble outside of vacuum
  - Install in vacuum system
  - Complete assembly/integration

- Task 5, Testing
  - Define test battery
  - Prepare a schedule
  - Perform defined tests
  - Analyze and report results

2.3 Single-active-stage with triple pendulum prototype

The Stanford SEI prototype is a stiff, single layer active platform controlled in six degrees of freedom with a pair of triple pendulums suspended from it. The goals of the prototype are:

- Demonstrate 6 degree-of-freedom (DOF) performance of a stiff active platform with a) collocated sensors and actuators and b) modern Multi-Input Multi-Output (MIMO) control design.

- Demonstrate sensor blending of relative displacement sensors and inertial sensors.

- Validate the computer code used to model the reference design for LIGO II.

- Demonstrate performance improvement from feed-forward control.

- Demonstrate reliable performance of a system with both an active platform and multi-element pendulums.

- Develop reallocation techniques to offload control authority from pendulum actuators to platform actuators.

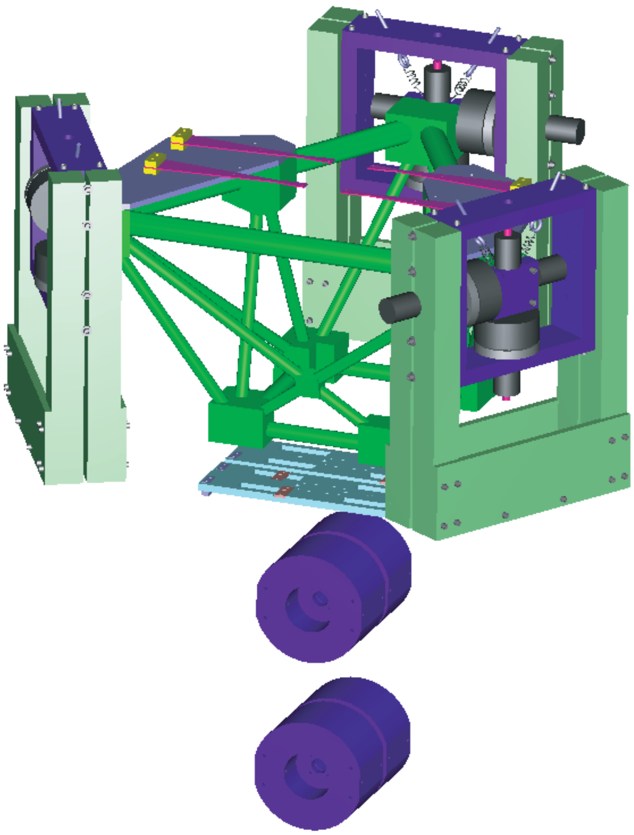

Figure 6: Drawing of the Stanford Active Platform and pendulums Prototype. A single-layer active seismic isolation platform supports two triple pendulums of a design based closely on the GEO triple pendulum.

- Implement watchdog schemes for oversight of the control system operation modes.

These goals are listed in approximate chronological order. We plan to work on the first five points before April, and points 6 and 7 after April. A computer rendering of the fully assembled prototype is shown in figure 6.

2.3.1 Collocated sensors/actuators and modern MIMO control design

The active platform was designed to exploit several lessons we have learned about control. These can be illustrated by examination of the three isolation pods at the corners of the active platform.

Each pod contains two sets of sensors and actuators, one horizontal and one vertical, so the three pods control all six degrees of freedom of the platform. The sensors and actuators are said to be collocated because the motion of the actuated point is directly measured by the sensor. We can see in figure CCC that the sensors and actuators are aligned and there are no intermediate dynamics in the block of metal which connects them (in the frequency

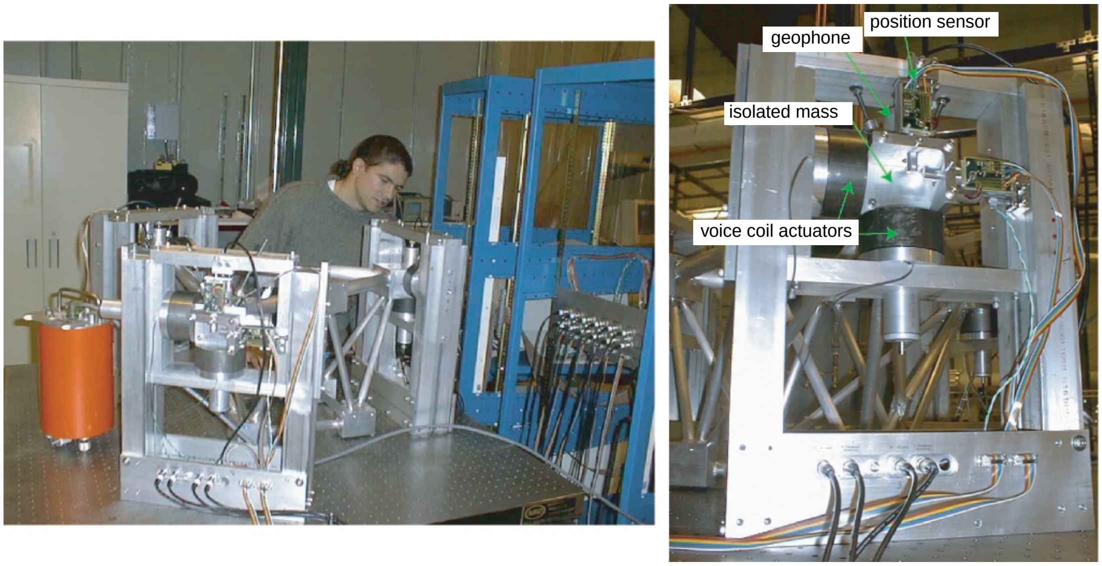

Figure 7: Corwin Hardham and the single layer active platform. The aluminum space frame in the center of the structure is isolated and controlled. Each of the three corners are controlled in 2 DOF by an isolation pod, giving full 6 DOF control of the structure.

range of interest). By collocating the sensors and actuators, we planned to greatly simplify the control problem, because reasonable isolation should be possible with 6 independent single input, single output (SISO) loops. MIMO control can then be used to increase the system's tolerance to drift and misalignment, improving robustness. In the tests we have run so far on the three vertical channels, this is the case. By comparing the SISO and MIMO performance, we are also gaining insight about the relative importance of design details for the reference design.

In the next several weeks we will demonstrate MIMO performance on all 6 degrees of freedom for the single layer active platform, and compare that result with the SISO performance.

The MIMO development is significantly accelerated by the real-time development system we are using for the Stanford prototype (and for the stiff double active stage prototype). The servo control is implemented with a dSpace real-time computer. The dSpace interface allows servo controllers to be developed in Simulink with the modern control tools of Matlab. These controllers can be immediately applied to the experiment (by selecting the "build" option in Simulink). THis tight integration between modeling software and test hardware is expected to allow a fairly short compensation design process.

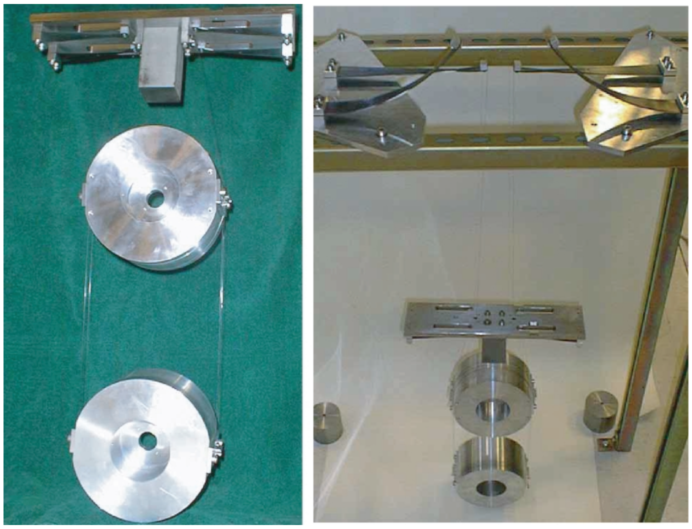

Figure 8: Triple pendulum being balanced in test fixture. The design is closely based on drawings from GEO 600, and the blade springs were made by the JILA instrument shop.

2.3.2 Validation of the LIGO-II reference design computer code

One of the most important results of the MIMO performance demonstration will come from tuning the modeling program. Our goal is to use this physics based model of the system to accurately predict the behavior of the controlled prototype. If the prototype works as the model predicts, we will improve our confidence in our model and in our ability to design controllers using our model. We can already reproduce the vertical plant dynamics with the model reasonably well, and we will soon be using the model to design MIMO controllers.

2.3.3 Demonstration of blending of displacement with inertial sensors

The sensor blending in our prototype is running successfully. Sensor blending is important because active platforms all rely both on inertial sensors and on relative displacement sensors to the previous stages. Inertial instruments can not work at zero frequency. However, by using non-inertial (i.e. relative) sensors at low frequency, we can gain many advantages, including:

- Eliminate the low frequency cross-over in the isolation loops, improving stability.
- Improve performance of the isolation system by requiring that inertial sensors only provide useful information in their sensitive frequency band. This is a direct result of eliminating the low frequency crossover.
- Provide alignment information.

At Stanford, we have been combining sensor outputs for some time, using a technique called complementary filtering (see, for example, reference [4]). Using this method the position sensor and seismometer are combined to create a "super-sensor" that provides useful information at both high and low frequency.

The single layer active platform uses 4.5 Hz geophones as inertial sensors, and optical sensors as the relative displacement sensors. These sensors can be seen in Figure 7. Figure 9 demonstrates an implementation of complementary filtering. In this figure, the geophone seismometer, shown in green, is significantly attenuated below 4.5 Hz because of the nature of that inertial sensor, but some loop shaping is performed between 1 and 5 Hz to achieve the necessary phase margins between the sensors. Low-frequency information is obtained from the relative position sensor (in red). Although the relative sensor provides many benefits, feedback based on information from the position sensor causes the platform to follow ground motion, which bypasses the isolation. Therefore, a low pass filter is applied to the position sensor information at low frequency (as low as possible) prior to its combination with seismometer data. The final combination (blue) represents the super-sensor which is used for feedback control.

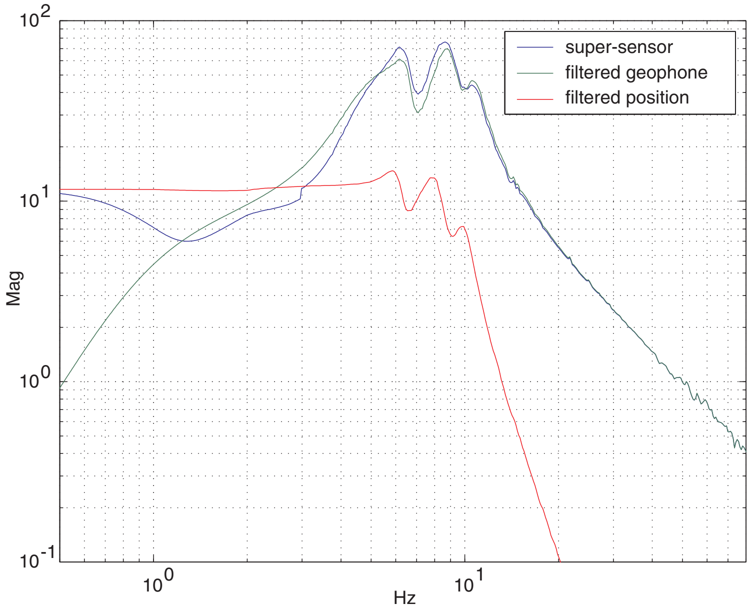

Figure 9: Transfer function from the coil drive to the filtered sensor output. This illustrates the complementary filtering used to combine the geophone signal and the relative position signal.

2.3.4 Demonstration of performance improvement from feed-forward control

We will be implementing feed-forward control and sensor correction on the vertical motion of the single layer platform. Sensor correction is a technique that (in our case) "corrects" a signal from a relative displacement sensor to account for the motion of the stage's motion.

Feed-forward is a technique that removes noise from the system by applying a force calculated to null the transmission of the source noise, based on measurements of that noise and knowledge of how it propagates through the system.

A signal from a high quality geophone will be used to correct the optical displacement sensors, and improve the performance of the system between .7 Hz and 10 Hz. These are the frequencies for which the S-13 sensor we have available is very well suited. The reference design will have an operating mode available that will incorporate both feed-forward and feedback to help improve the isolation, especially during periods of exceptional environmental noise. Since feed-forward corrections improve performance but do not generally impact stability, we believe that the best use of our resources is to implement only a single degree of freedom. This will give us experience with feed-forward in our isolation system, and help our model validation with only minimal hardware. Further studies of feed-forward control and sensor correction will be pursued after April as we try to get the maximum performance from the prototype.

2.3.5 Demonstration of reliable performance of a system with both an active platform and multi-element pendulums

In LIGO II, the isolation platform should provide a quiet, robust platform on which to mount the optics pendulum. One of the advantages of a stiff, active platform is that it will not interact badly with the local control servos of the multiple pendulums which it is designed to support. We are building a pair of triple pendulums, seen in figure EEE, based on the GEO 600 design. The pendulums will hang from the single active stage so that we can investigate two issues: first, what are the requirements for maintaining robust performance of both the active stage isolation servos and the multiple pendulum local damping servos in the presence of interactions, and second, how can we optimize the reallocation of control authority between the pendulum and the active platform to maintain interferometer lock while making best use of the dynamic range, bandwidth, and noise performance of the set of available actuators.

We plan to study the control interaction question before April. we believe this is a very import question to address, and that it will demonstrate a clear advantage of the stiff team approach.

We will also add the triple pendulums to the model and try to predict the performance of that complicated system. We believe that if we can accurately predict the transfer functions of a triple pendulum suspended from a single stiff platform, we will have a good enough grasp of the fundamental issues that we can make reasonable statements about the control of the reference design.

2.3.6 Development of control reallocation techniques

The ability to easily offload control authority from the actuators in the multiple pendulums to the larger actuators in the active platform is a benefit of the stiff active approach. This control reallocation can easily be tested and developed with the Stanford isolation prototype. However, we have decided to pursue this research during the summer.

2.3.7 Implementation of watchdog schemes for oversight of SEI operation modes

The LIGO control system and the prototype systems run on real time control hardware. This will allow us to monitor the servo performance and change operation modes in response to various events. We will certainly want different control modes for lock acquisition, standard data collection , and system performance tests. Safety modes would be useful in the event of external power loss or large seismic events. The ability to safely and easily change the operation mode of the system provide various safe modes is an advantage of a system with good control performance. We will be investigating various watchdog schemes later in the year .

References

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