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Technical Note **LIGO-T950058-00 -** **R** 8/31/95

DESIGN REPORT OF THE 40M TEST MASS SUSPENSION PROTOTYPE

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1 INTRODUCTION

This document describes the design and features of the prototype suspension system[1] for the 40m test mass.

2 FUNCTION

The main functions of the 40m test mass suspension are:

- Suspend a test mass and allow it to move freely horizontally for detection of gravitational waves.
- Isolate a test mass from ground motion by suspending it.
- Damp a test mass's motion in position and orientation using the local suspension's sensors and actuators.
- Provide a switch and control inputs for the optical lever global control[2].
- Provide control inputs for applying forces to a test mass in response to the interferometer LSC signals.
- Protect a test mass and magnet/standoff assembly by limiting motion from external disturbance.
- Hold a test mass firmly during transfer of the suspension assembly into the chamber.

3 FEATURES OF DESIGN

Our experience on the current 40m suspension, the 12m mode cleaner suspension, and the PNI suspension has lead us to the following features of the new suspension design.

- One-body modular type suspension assembly
- Single loop of wire
- No control block
- Grooved wire standoff and guide rod
- Edge sensor with no vane
- No active stabilization of LED intensity
- No preamplifier in the vacuum
- Cradle type safety cage
- Easy access to safety stop
- Low control noise
- Low eddy current damping

1. After the prototype of the 40m test mass suspension is installed and tested in the 40m interferometer, the design will be further optimized for the remaining test mass and the beamsplitter suspensions.
2. It is intended that the 40m suspension doesn't require the optical lever sensor signal to control the test mass in terms of both the S/N ratio and the residual fluctuation. Nevertheless it is considered to be wise to incorporate the switch and control input for the optical lever control for insurance.

4 CONCEPTUAL DESIGN

4.1. Mechanical System

The conceptual design of the mechanical part of the 40m test mass suspension is shown in Fig. 1. The test mass is suspended by a single loop wire (with the wire standoffs and the guide rods) from the suspension block, which is mounted on the top plate of the suspension support structure. The test mass has six magnet/standoff assemblies glued to the mass, and five sensor/actuator heads are supported by the head holder, which is mounted on the suspension support structure. The test mass is protected by the safety cage and the safety bar with several safety stops; the safety cage and the safety bar are also mounted on the suspension support structure. The whole assembly including a test mass weighs 12.6 kg[1].

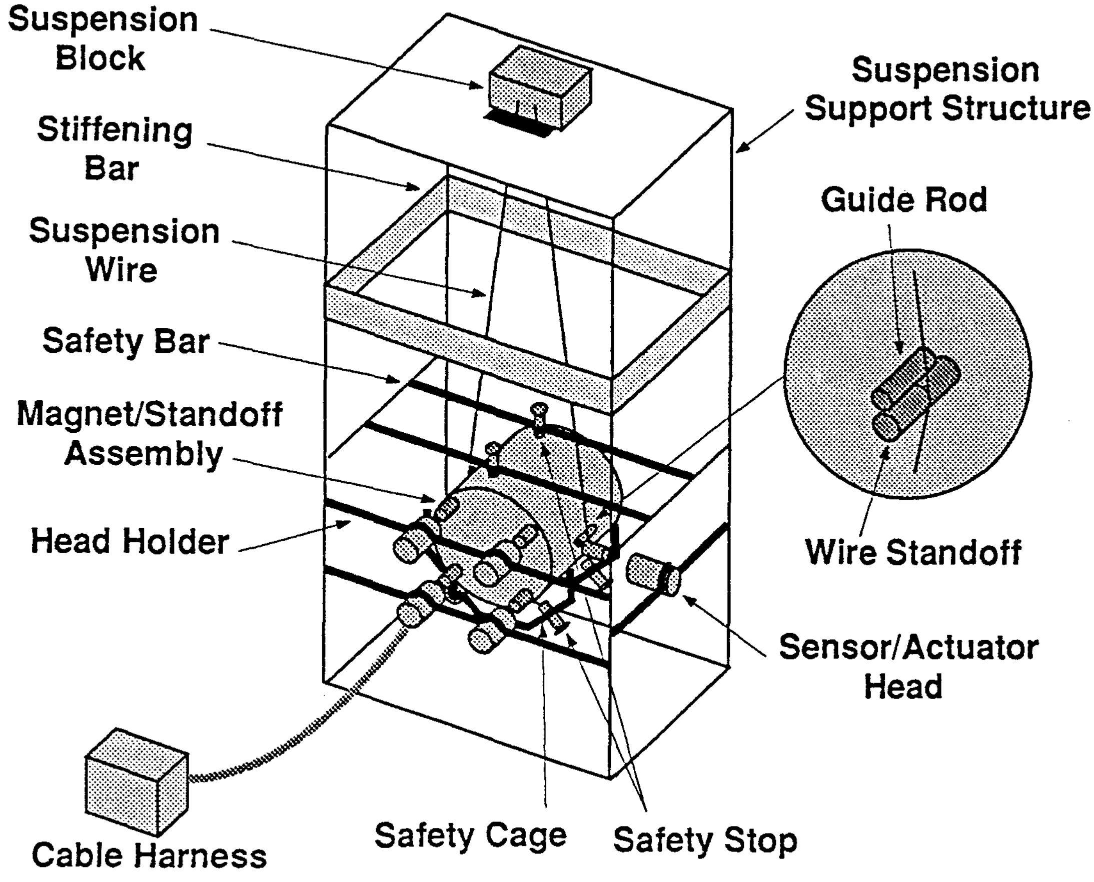


Figure 1: Conceptual design of the mechanical part of the 40m test mass suspension.

1. The stack was designed for a load from 20 to 80 kg (according to Lisa Sievers).

4.1.1. Suspension Support Structure

The suspension support structure is a rectangular frame on which, the suspension block, the head holder, the safety cage, and the safety bar are mounted. This modular support structure makes it possible to assemble the system and balance the test mass on a clean bench and then to transfer it into the chamber without changing the relative position between the test mass and the sensor/actuator head.

All the resonant frequencies of the suspension support structure are calculated to be above 127 Hz with four stiffening bars in the middle of the suspension support structure legs, which ensures that the seismic noise is not contaminated by the resonant peaks of the suspension support structure below 127 Hz.

Transverse separation of the vertical frames is wide enough so that it is easy to get access to the safety screw, and still small enough so that the frames are not in the way of the optical lever beam and the folding mirrors for it.

Longitudinal separation of the vertical frames is wide enough so that it is possible to see the mirror surface directly from side.

Yaw alignment of the suspension support structure inside a chamber is done using a conventional screw-clamp.

- Height: 476.8 mm (18.77")
- Transverse Width: 241.3 mm (9.5")
- Longitudinal Width: 162.6 mm (6.4")
- Material: Aluminum
- The lowest resonance frequency: 127 Hz with four stiffening bars in the middle of the suspension support structure legs

4.1.2. Test Mass

The current test masses are used with their wedge orientation maintained.

- Material: Fused Silica
- Size: 101.6 mmD x 88.9 mm (4"D x 3.5"L)
- Wedge: 2 degrees +/- 30 minutes (end mass), 25-30 minutes (vertex mass), horizontally oriented.
- Height of the center of the test mass relative to the upper surface of the stack top plate: 139.7 mm (5.5")

4.1.3. Wire

A single loop wire is used.

- Type: Steel music wire
- Diameter: 91 μm (0.0036")
- Measured breaking force: 3.6-3.8 kgf with one loop

4.1.4. Suspension Block

The wire is hung down from the suspension block, which is mounted on the top plate of the suspension support structure. The suspension block has two guide pins and a clamp so that the distance of the wire at the suspension block (d_{yaw} defined in 4.1.6.) may be maintained properly.

4.1.5. Wire Standoff and Guide Rod

A small aluminum rod is placed between the wire and the test mass as a standoff. The wire standoff has a groove on it so that the wire doesn't slip on the rod, which assures the stable balancing of the test mass. A smaller quartz rod is attached to the mass to guide and position the wire standoff, to aid in balancing the test mass in pitch orientation.

- Wire standoff
  - Material: Aluminum
  - Size: 1.0 mmD x 4.8 mmL (0.039"D x 0.19"L)
  - Groove: 0.004"W, 90 degree 0.001"Rmax
- Guide rod
  - Material: Quartz
  - Size: 0.6 mmD x 3.3 mmL (0.025"D x 0.13"L)

4.1.6. Suspension Configuration

Definition of parameters of suspension configuration is shown in Fig. 2.

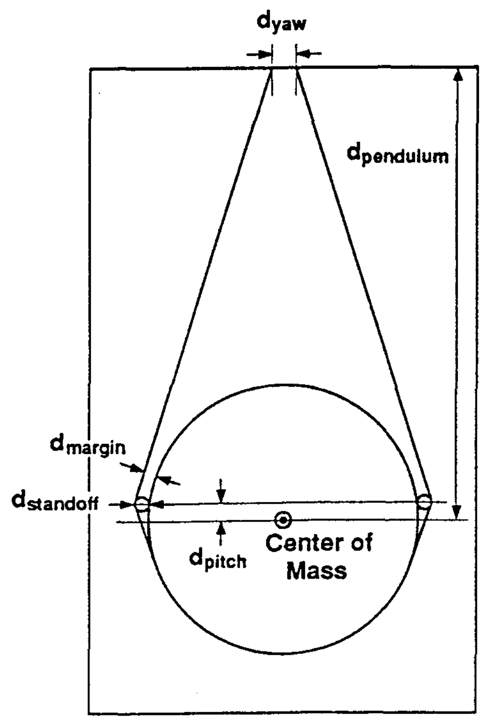


Figure 2: Definition of parameters for the suspension configuration.

Two types of suspension configurations are possible: Type I (default) and Type II (possible modification) Configuration parameters and the pendulum, pitch, and yaw resonance frequencies are shown in Table 1 as well as the wire resonance frequencies for each type of configuration.[1]

Table 1: Two types of suspension configuration.

Physical Quantity		*Type I*	*Type II*
Pendulum Resonance Frequency		0.84 Hz	0.84 Hz
Pitch Resonance Frequency		0.50 Hz	0.75 Hz
Yaw Resonance Frequency		0.60 Hz	0.73 Hz
$d_{pendulum}$		35 cm	35 cm
d_{pitch}		1.3 mm	2.9 mm
d_{yaw}		26 mm	38.5 mm
$d_{standoff}$		1.0 mmD	1 mmD
d_{margin}		0.8 mm	1.0 mm
Wire	Violin Mode Frequency	557 Hz	556 Hz
	Vertical Resonance Frequency	11.1 Hz	11.1 Hz

4.1.7. Magnet/Standoff Assembly

Six magnet/standoff assemblies are attached on the test mass: four on the back surface and two on the side surface of the test mass. The magnets are placed so that polarity of the magnets is located alternately to prevent the mass from being shaken in position and orientation by time-varying magnetic field.

- Magnet
  - Material: Nd:Fe:B (NEO, Curie temperature 337 C)
  - Size: 1.9 mmD x 3.2 mmL (0.075"D x 0.125"L)
- Standoff
  - Material: aluminum
  - Size: 1.0 mmD x 2.0 mmL (0.04"D x 0.08"L)

1. Assumptions are wire density of 7.8334 g/cm^3 and Young's modulus for the wire of 2.068 x 10^11 N/m^2.

4.1.8. Sensor/Actuator Head

The sensor/actuator head consists of a pair of an LED and a photodiode, a coil, and a housing. Five sensor/actuator heads are supported by the head holders (which are mounted on the suspension support structure) so that each sensor/actuator head is located properly along the corresponding magnet/standoff assembly: four sensor/actuator heads on back, and one sensor/actuator head on side.

The LED-photodiode system senses the shadow of the magnet, thus position of the test mass. The current in the coil actuates the magnet, thus the test mass. The system is illustrated in Fig. 3.

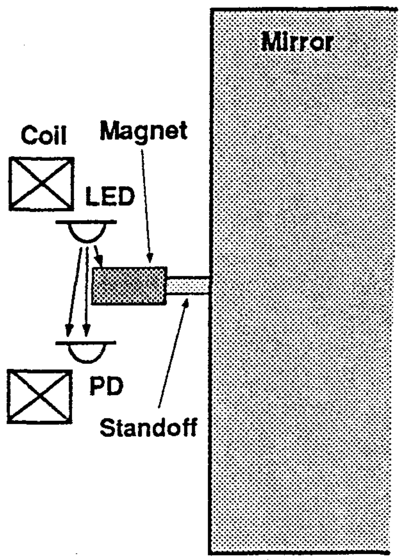


Figure 3: The sensor/actuator head and the magnet/standoff assembly.

- LED: TLN107A, Toshiba, no outgas was observed after being baked at 70c
- PD: TPS703A, Toshiba, no outgas was observed after being baked at 70c
  - Distance between PD and LED: 6 mm
- Coil
  - Wire size: 0.22 mmD
  - Coil size: 7.66 mmID, 12.66 mmOD, 5 mmL
- Housing
  - Material: Macor[1]
  - Size: 25.3 mmOD x 45.9 mmL
  - Wire clamp: Wires wrapped around a screw which is threaded into back of the head housing.

1. Machinable glass ceramic: manufactured by Corning.

4.1.9. Head Holder

The head holders are mounted on the suspension support structure. The head holder has a hole with guide pins and a set screw for the sensor/actuator head so that the sensor/actuator head can be placed and fixed properly without changing its position. The head holder, which is made of stainless, is located far enough from the magnets on the test mass so that the thermal noise caused by the eddy current damping is negligible.

4.1.10. Safety Cage, Safety Bar, and Safety Stop

The safety cage and the safety bar, which have safety stops, are used to restrain the test mass motion and to protect it from damage. They are also used to hold the test mass firmly during assembly and installation.

4.1.11. Cable Harness

The cable harness for the cables from the sensor/actuator heads are mounted on the stack top plate.

4.1.12. Fixture for Magnet/Standoff Assembly and Guide Rod

A monolithic fixture is used to set the six magnet/standoff assemblies and the two guide rods for the wire standoff.

4.1.13. Procedure for Balancing Test Mass

The procedure for balancing the test mass is as follows:

1. Assemble the suspension support structure and mount the suspension block, the head holder, and the safety cage properly on the suspension support structure.
2. Place the test mass (on which the guide rods, the magnets, and the standoffs have been glued.) on the safety cage roughly to where it should be, using the safety stops to hold in place.
3. Mount the sensor/actuator head on the head holder.
4. Adjust the test mass position with the sensor/actuator head as reference using the safety stop.
5. Mount the safety bar on the suspension support structure and set the safety stop 1 mm off the test mass.
6. Sling the test mass with the wire standoff inserted between the test mass and the wire from the suspension block so that the test mass floats off from the safety stop infinitesimally.
7. Loosen all the safety stop of the safety cage by 1 mm.
8. Balance the test mass by adjusting the position of the wire standoff[1] along the guide rod by the PZT buzzer with the help of the optical lever.
9. Glue both end of the wire standoff.

1. The balance of the test mass also depends on the position of the wire on the lower rim. It is possible to make the wire on the lower rim quite straight by rotating the mass back and forth around the beam axis.

4.2. Control System

The schematic diagram of the control system of the 40m test mass suspension is shown in Fig. 4. The position and angle of the test mass are detected by the edge sensor which consist of a pair of LED and photodiode. Either this signal or a signal from the optical lever sensor (40m) is filter/amplified and fed back to the coil to damp the test mass. A bias signal and an interferometer LSC signal are injected in the control loop.

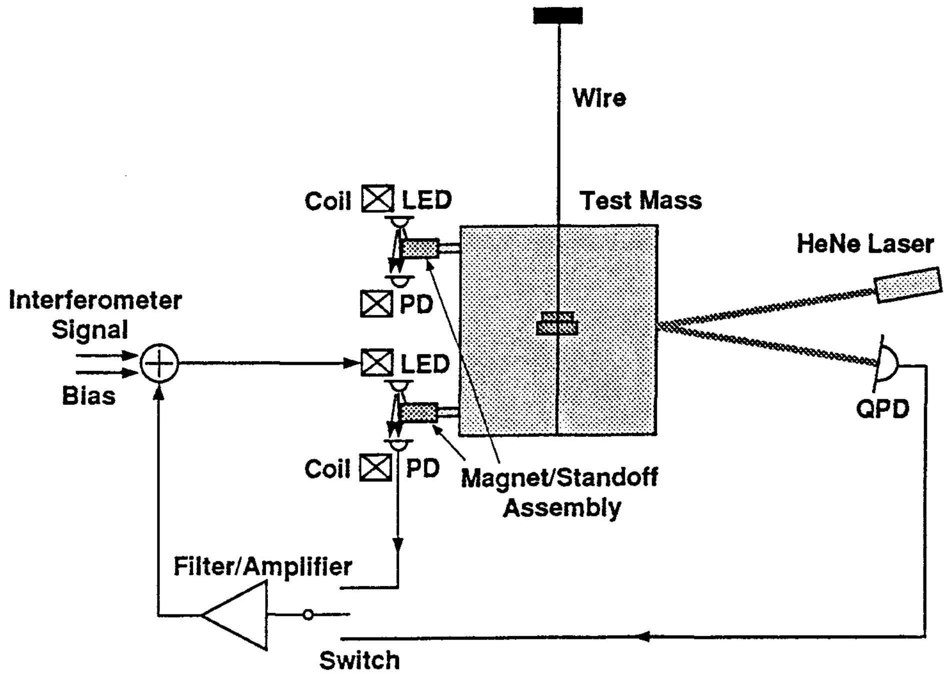


Figure 4: Schematic diagram of the control system for the 40m test mass suspension.

4.2.1. Sensor and Actuator

The LED-photodiode system senses the position of the magnet. The current in the coil applies force to the magnet.

- Sensor
  - LED current: 10 mA
  - PD current: 100 μA_{max} (50 $\mu A_{nominal}$)
  - Sensitivity: 70 µA/mm per head
  - Range: 0.6 mm_{pp} (for 90% of maximum)
- Actuator
  - Current-force coefficient: approximately 0.02 N/A per head[1]

1. Estimated from the measured value of 0.045 N/A for the 12m MC suspension (300 turns, Nd:Fe:B 0.125"D x 0.175"L).

4.2.2. Electronic System

The schematic diagram of the electronic system of the suspension control is shown in Fig.5. The photocurrent in the photodiode is transformed into voltages and then by input matrix converted into position, pitch, yaw and side signal. The switch makes it possible to choose either these suspension's sensor signal or global signal. The signal is filter-amplified and summed with bias signal or test signal, then by output matrix distributed to each coil through a low-pass filter. The length sensing control signal is applied to the coil at the last stage.

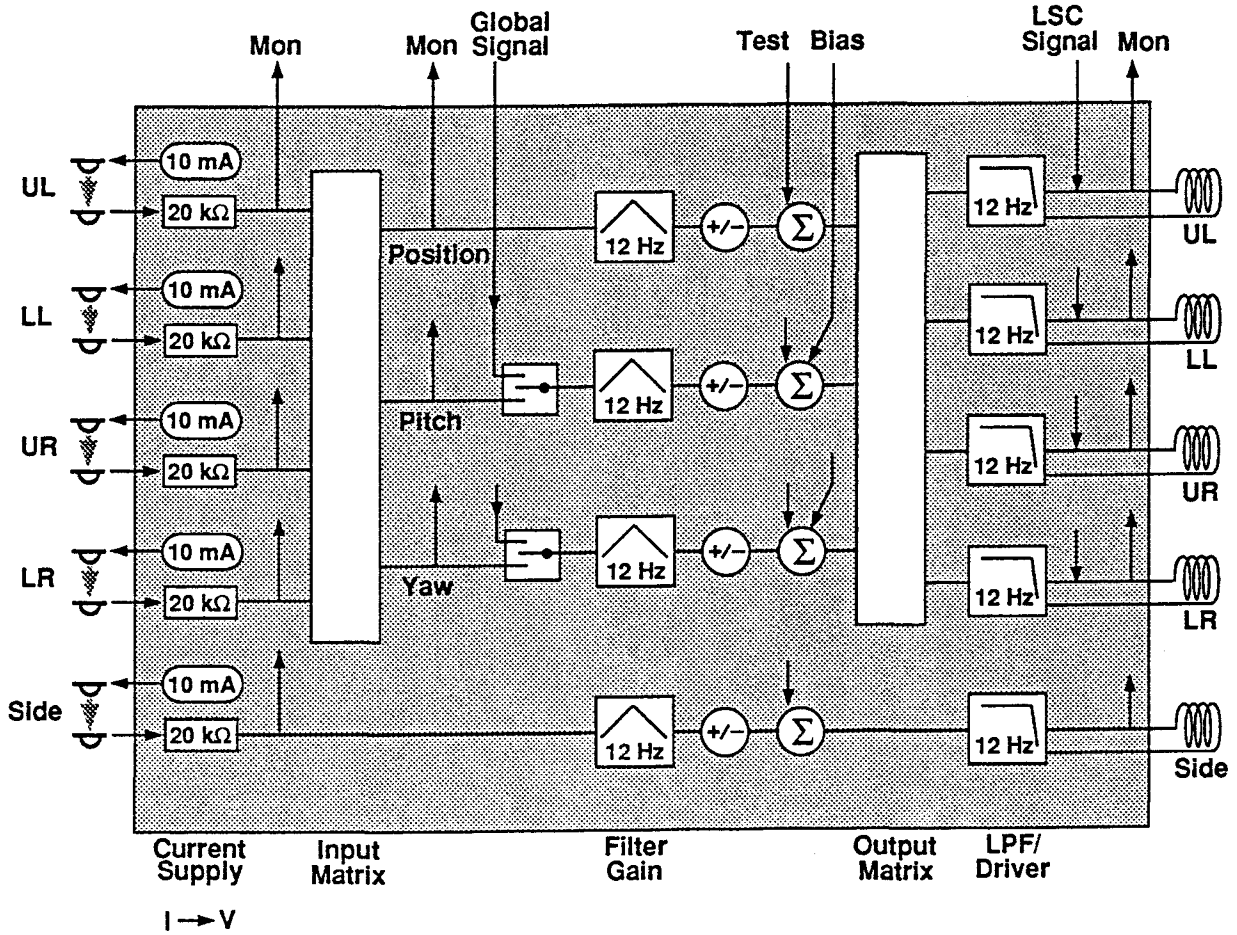


Figure 5: Schematic diagram of the electronic system of the suspension control.

4.2.3. Output Driver and LSC Signal Injection

A current-source type driver is used; as shown in Fig. 6, the coil is placed inside the feedback loop of the OP-amplifier. The LSC signal is injected into the inverting input of the OP-amplifier. The voltage at the right end of the series resistor (R_3) is monitored as the LSC feedback signal. R_1 is 1 kΩ, R_2 is 100 Ω, and R_3 is 100 Ω during lock acquisition and switched to 1 kΩ for signal monitor.

This configuration has several advantages[1] as follows:

(1) Effect of any noise produced before the summing junction including the Johnson noise of R_1 and R_2 is suppressed by monitoring the LSC feedback signal afterward.

(2) Because of the high impedance looking from the coil, no pick-up current can flow in the coil.

(3) Monitor signal is free from any pick-up existing in the long loop containing the coil.

(4) Because of the high impedance looking from the coil, vibration of the coil with respect to the magnet doesn't cause eddy current; the mass is not dragged.

(5) The maximum current for the LSC signal is big enough with R_2=100 Ω and R_3=100 Ω for acquisition.

(6) The signal to noise ratio at the monitor point is good enough with R_3=1 kΩ.

(7) It is possible to switch between the above-mentioned acquisition mode and monitor mode without disturbing both the LSC system and the damping control system.

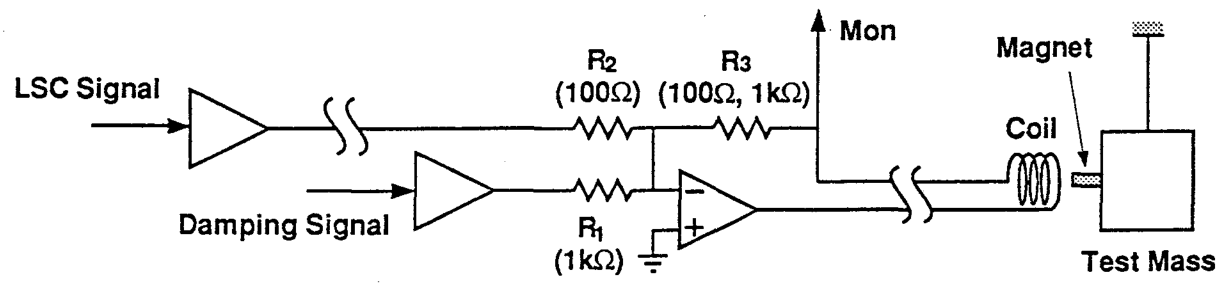


Figure 6: Schematic diagram of the output driver and the LSC signal injection.

1. The most important advantage might look seemingly that there is no degradation in the thermal noise due to eddy current damping because of the high impedance looking from the coil. But it is not true. Without the LSC signal, The Johnson noise of R_1 causes the current into the coil, which results in the identical thermal noise degradation. With the LSC signal, the monitor signal can reduce the effect of R_1, but it sees the Johnson noise of R_2 as a readout noise instead, which is equivalent to the thermal noise degradation.

4.2.4. Configuration of Electronic Modules, Cables, and Cable Harness

Fig. 7 shows the configuration of the electronic modules, cables, and a cable harness (not including the optical lever signal) of the 40m test mass suspension. The cable from each edge sensor is gathered at the cable harness on the stack top plate, and then the cable from the harness is led to the cable connector of the chamber via each stage of the stack. A preamplifier satellite is located by the chamber and the control module is in the rack near the chamber. A fine bias module is placed in the center rack.

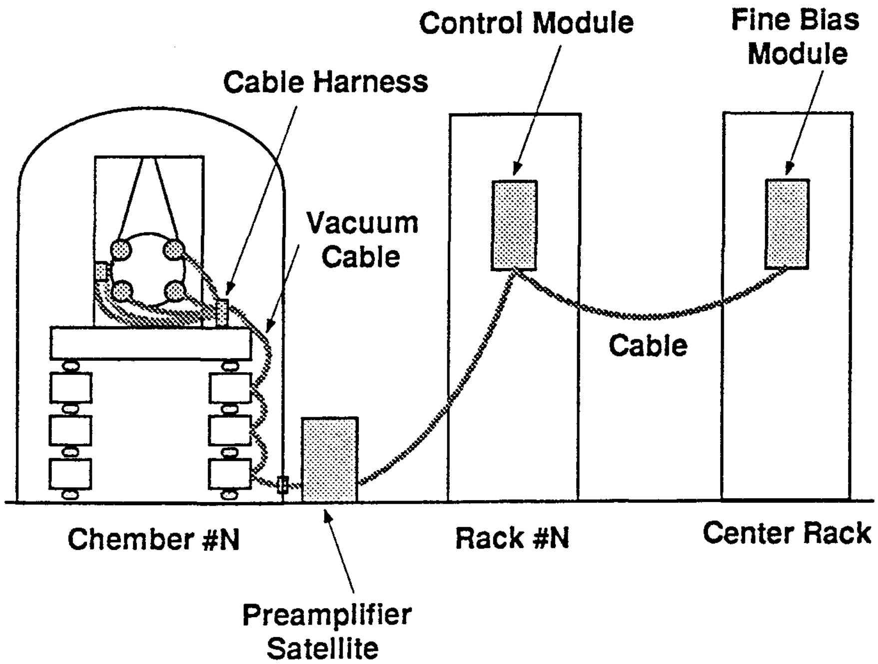


Figure 7: Electrical part of the 40m test mass suspension system.

4.2.5. Servo Topology

Fig. 8 shows a block diagram of the 40m suspension damping control system for each degree of freedom. Force (or torque, depending on the degree of freedom) applied to the test mass produces displacement (or angle) of the test mass by the transfer function which has two almost imaginary poles at the resonance frequency of the pendulum. The displacement (or angle) is then detected by the sensor, producing voltages with a frequency-independent coefficient. The voltage signal is then filter/amplified by a transfer function which consists of a zero at DC and 10 pole Chebyshev (1 dB) 12 Hz low pass filter. This feedback signal produces force (or torque) with a frequency-independent coefficient of the actuator.

With this configuration, when the loop gain is set appropriately, the closed loop transfer function, from force (torque) to displacement (angle) doesn't have a bump in gain around the resonance frequency; the phase delay of the servo loop around the resonance frequency is appropriate.

The sensor noise is injected before the sensor transfer function. This noise is suppressed by the steep low pass filter. The driver noise and the Johnson noise is, on the other hand, injected after the filter/amplifier; they act on the test mass directly without being suppressed by the filter.

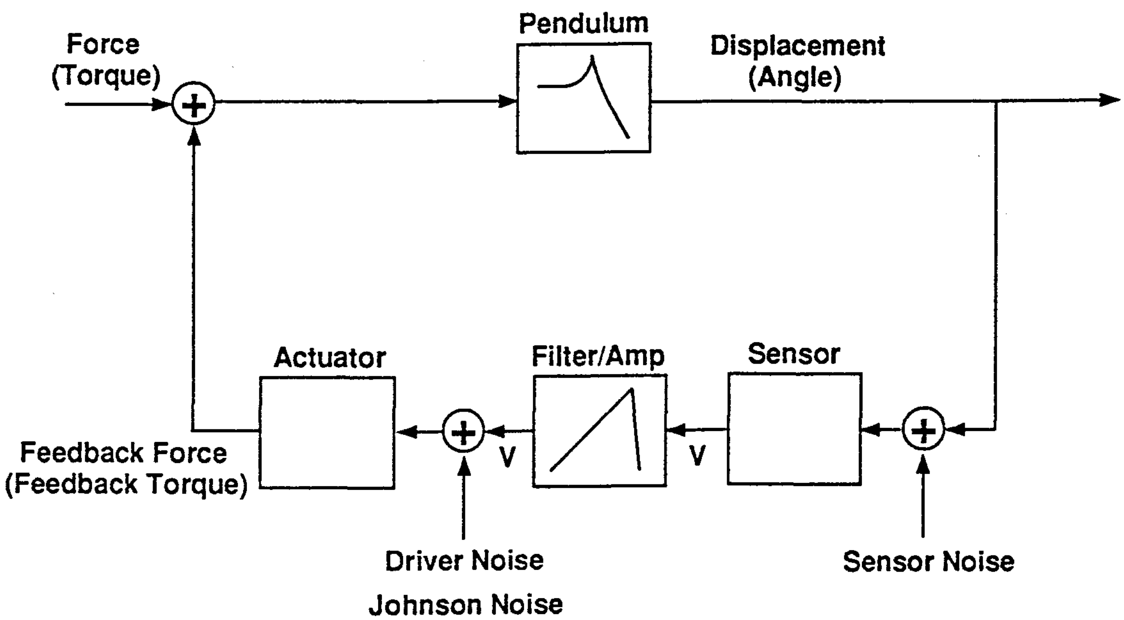


Figure 8: Block diagram of the 40m suspension damping control system together with typical noise sources.

4.2.6. Control Parameters

Each degree of freedom to be controlled has a different sensor and actuator sensitivity, and a different mechanical response coefficient, thus has a different electronic gain required for a pseudo-critical damping[1]. Table 2 summarizes such a control parameters for each degree of freedom. Each parameter (Pendulum, Sensor, Filter/Amp, and Actuator) corresponds to each transfer function shown in Fig. 8.

The filter/amp gain was obtained by the criteria:

Pendulum (@ DC) x Sensor x Filter/Amp (@ f_0) x Actuator = 1

Table 2: Control parameters for each degree of freedom.

Degree of Freedom	*Pendulum*		*Sensor (V/m or V/rad)*	*Filter/Amp $Gain_{elec}$ @ 1Hz*	*Actuator (N/V or Nm/V)*
	f_0(Hz)	*(m/N or rad/Nm) @DC*			
Position	0.84	2×10^{-2}	6×10^{3}	100	8×10^{-5}
Side	0.84	2×10^{-2}	2×10^{3}	1600	2×10^{-5}
Pitch	0.50	60	200	60	3×10^{-6}
Yaw	0.60	40	200	70	3×10^{-6}

1. The pseudo-critical damping is defined in this document to be a damping with a minimum gain which makes the closed loop transfer function in gain bumpless around the resonance frequency.

4.2.7. Sensor Noise

The sensor noise is dominated by the shot noise at the photodiode. It is attenuated by the steep low pass filter. Table 3 shows resultant displacement noise at 40 Hz caused by the sensor noise, together with sensor noise, loop gain, and coupling coefficient. The criteria to calculate the displacement noise is: Displacement Noise = Sensor Noise x Loop Gain x Coupling

Table 3: Sensor noise and the resultant displacement noise for each degree of freedom.

Degree of Freedom	*Sensor Noise (m/rHz or rad/rHz)*	*Loop Gain @ 40 Hz*	*Coupling*	*Displacement Noise @ 40 Hz (m/rHz)*
Position	3×10^{-11}	7×10^{-10}	1	2×10^{-20}
Side	6×10^{-11}	7×10^{-10}	< 0.1	$< 4 \times 10^{-21}$
Pitch	8×10^{-10}	4×10^{-10}	< 3 mm	$< 1 \times 10^{-21}$
Yaw	8×10^{-10}	4×10^{-10}	< 3 mm	$< 1 \times 10^{-21}$

4.2.8. Driver Noise and Johnson Noise

There is an inherent noise existing at the output of the driver, produced after the steep low pass filter, which causes displacement noise. Table 4 summarizes displacement noise caused by the driver noise and the Johnson noise for each degree of freedom. The criteria is:

Displacement Noise = Effective Driver Noise x Actuator/Pendulum x Coupling

Table 4: Driver noise and the resultant displacement noise for each degree of freedom.

Degree of Freedom	*Effective Driver Noise (V/rHz)*	*Actuator/ Pendulum @ 100 Hz (m/V or rad/V)*	*Coupling*	*Displacement Noise @ 100 Hz (m/rHz)*
Position	3×10^{-9}	1×10^{-10}	1	3×10^{-19}
Side	6×10^{-9}	3×10^{-11}	< 0.1	$< 2 \times 10^{-20}$
Pitch	3×10^{-9}	5×10^{-9}	< 3 mm	$< 5 \times 10^{-20}$
Yaw	3×10^{-9}	5×10^{-9}	< 3 mm	$< 5 \times 10^{-20}$

4.2.9. Range of Actuator

The range of the actuator for each degree of freedom is summarized in Table 5. The criteria to get the range is: Range = Driver Voltage x Actuator x Pendulum

Table 5: Range of actuator for each degree of freedom.

Degree of Freedom	*Driver Voltage (V_{pp})*	*Actuator (N/V or Nm/V)*	*Pendulum @ DC (m/N or rad/Nm)*	*Range @DC (m_{pp} or rad_{pp})*
Position	30	8×10^{-5}	2×10^{-2}	5×10^{-5}
Side	30	2×10^{-5}	2×10^{-2}	1×10^{-5}
Pitch	30	3×10^{-6}	60	5×10^{-3}
Yaw	30	3×10^{-6}	40	4×10^{-3}

4.2.10. Cross-coupling

A cross-coupling at the sensor/actuator produces a spurious path existing in parallel with the main path, and might end up causing oscillation or significant gain loss in the main servo loop, depending on the polarity and the cross-coupling factor. The most vulnerable cross-coupling in this system is the one from the side motion to the yaw motion. With α as a sensor cross-coupling, and β as an actuator cross-coupling, the criteria to avoid the mal functioning in this case is:$\alpha \times \beta << 0.3$

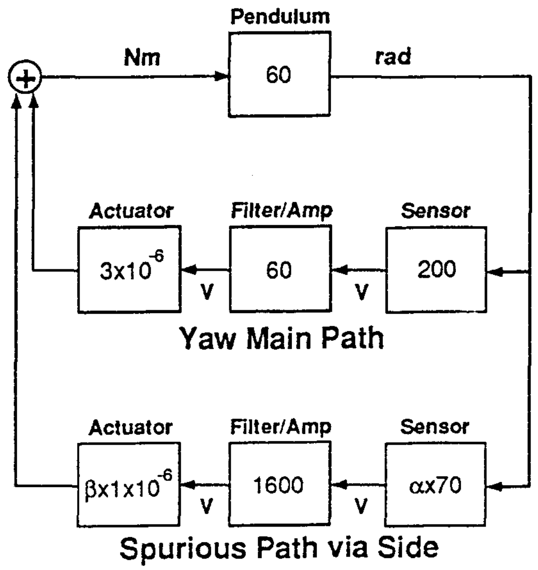


Figure 9: Spurious path via the side sensor actuator in parallel with the yaw main path.

5 TEST, INSTALLATION, AND EXPERIMENT

5.1. Test

The suspension system including the electrical system will be fully tested on the bench using the aluminum dummy mass. Especially damping function, range of actuators, noise performance will be checked to verify that they are met with the specifications.

5.2. Installation

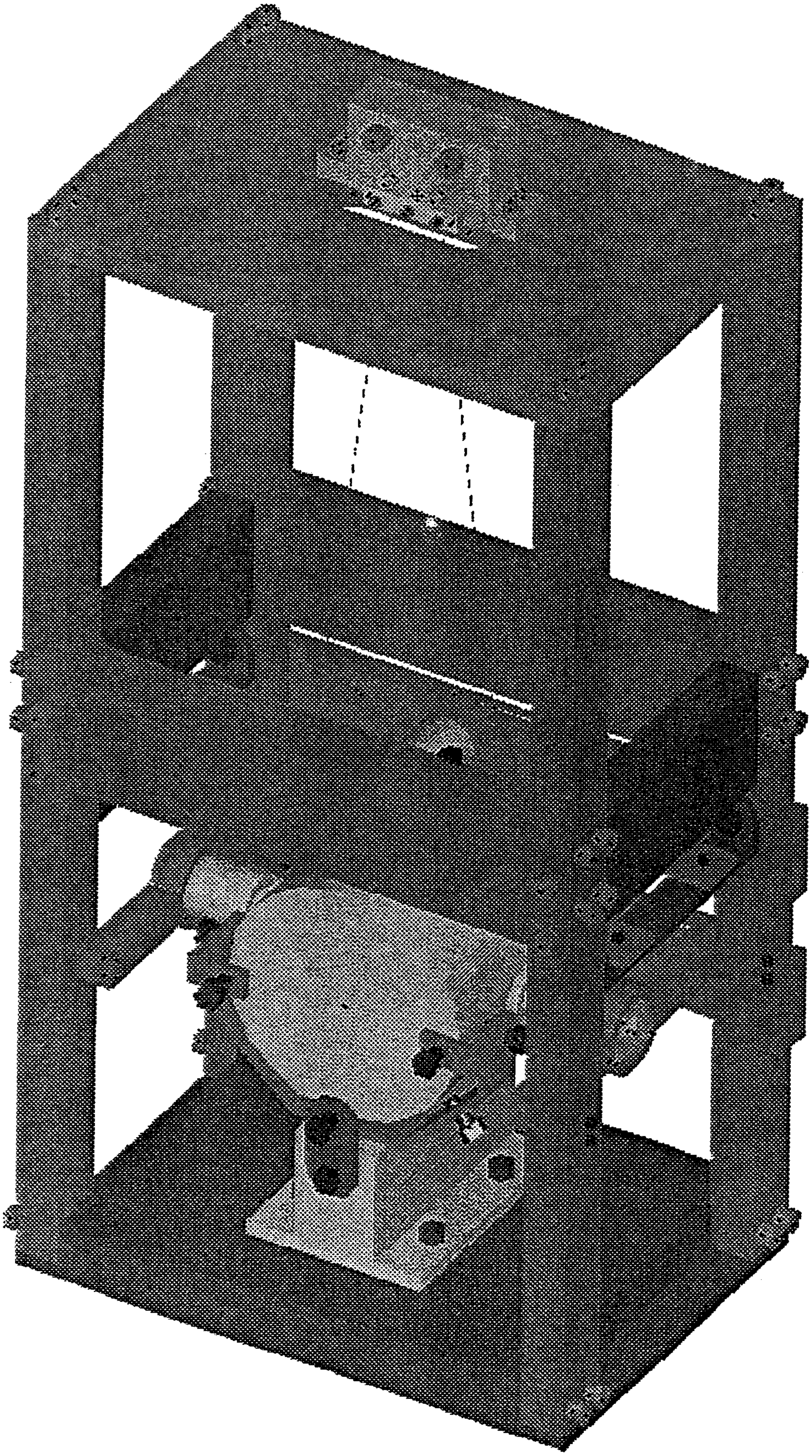
The south vertex suspension system will be replaced with the new suspension system. The mass which is currently used will be re-used.

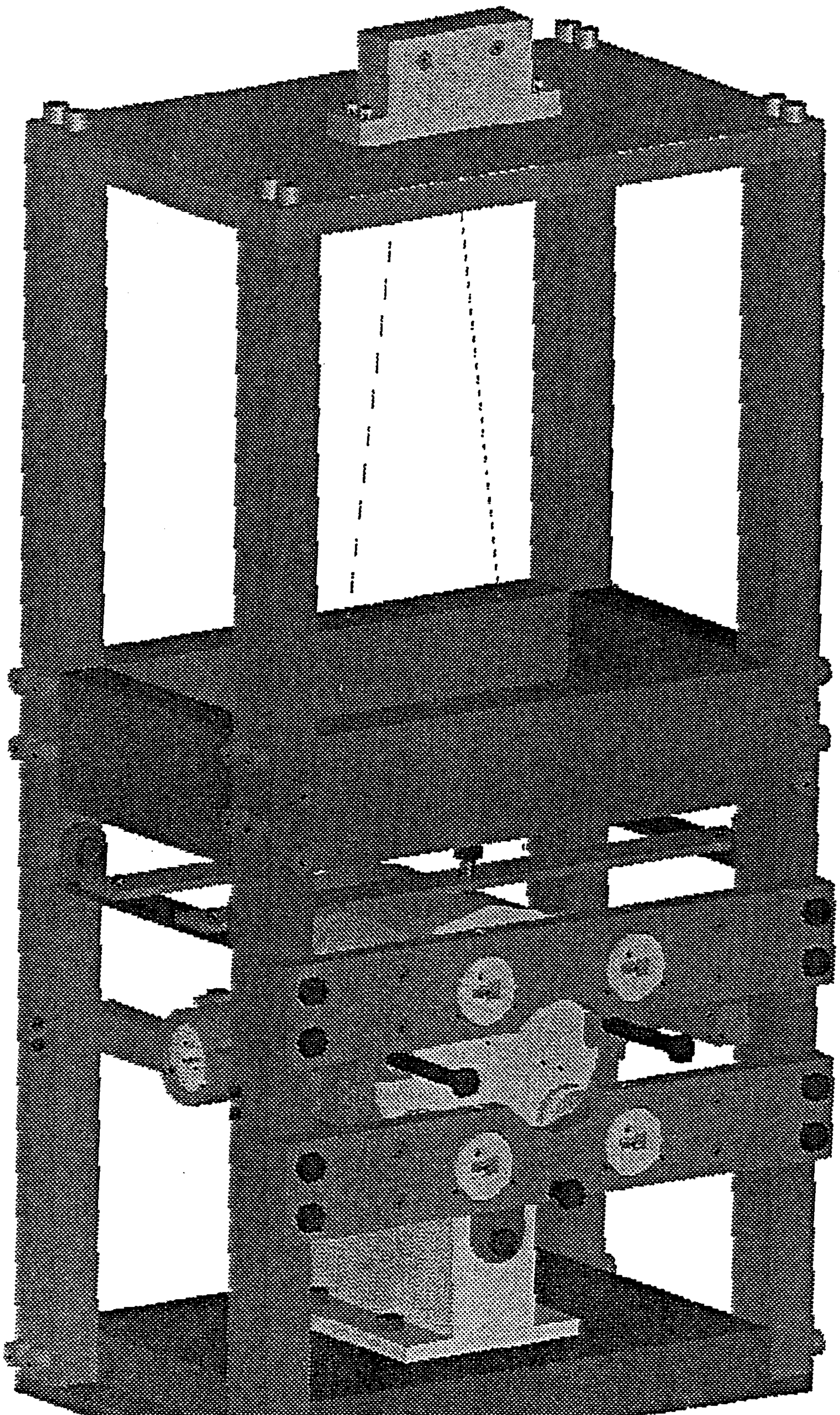
5.3. Experiment

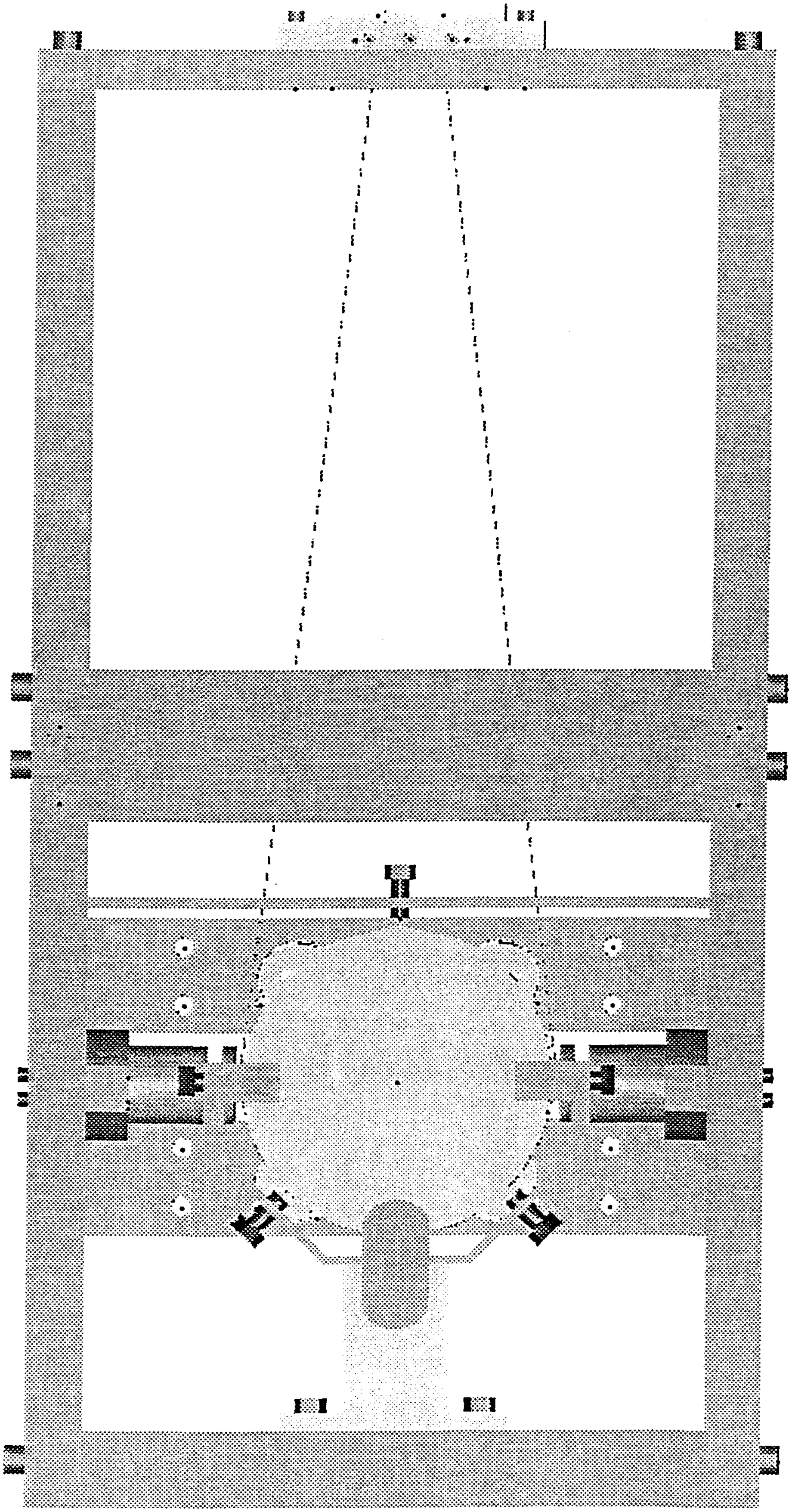
The new suspension system will be fully characterized in the 40m prototype. Whether or not the interferometer works fine with the new suspension system will be checked in terms of general performance and noise. Q of the violin mode and the internal mode will be also measured.

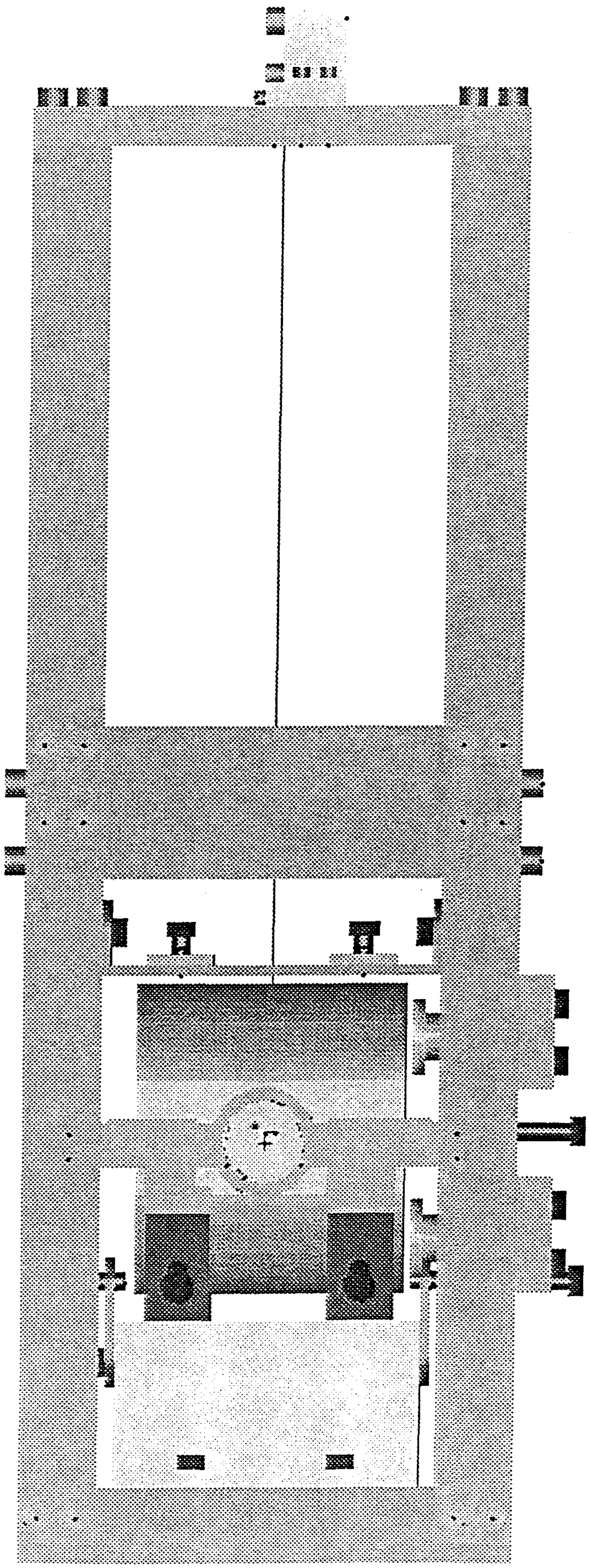
6 DETAIL DESIGN

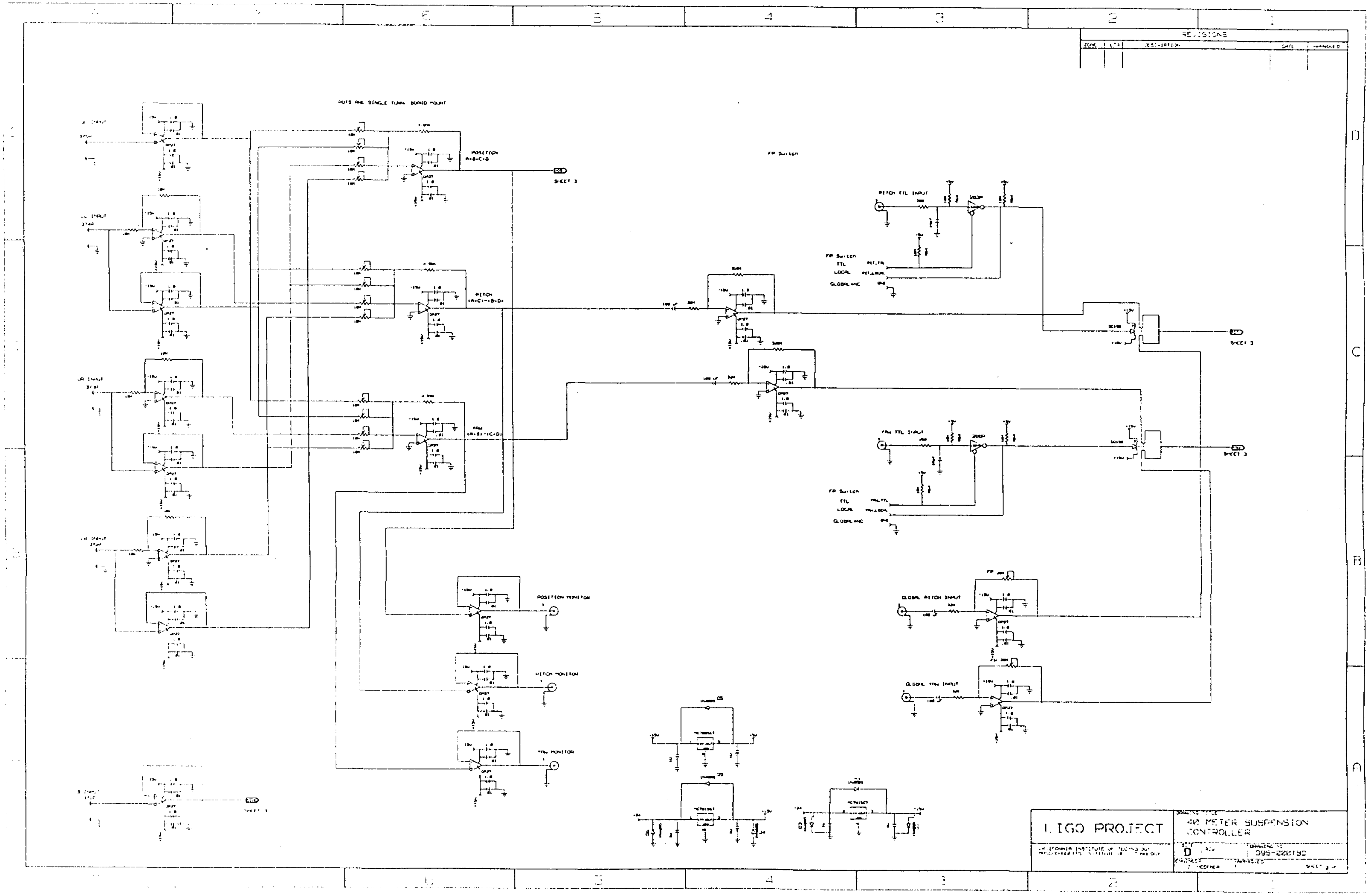
Attached in the following pages are detail designs of the mechanical system and the electronic system.







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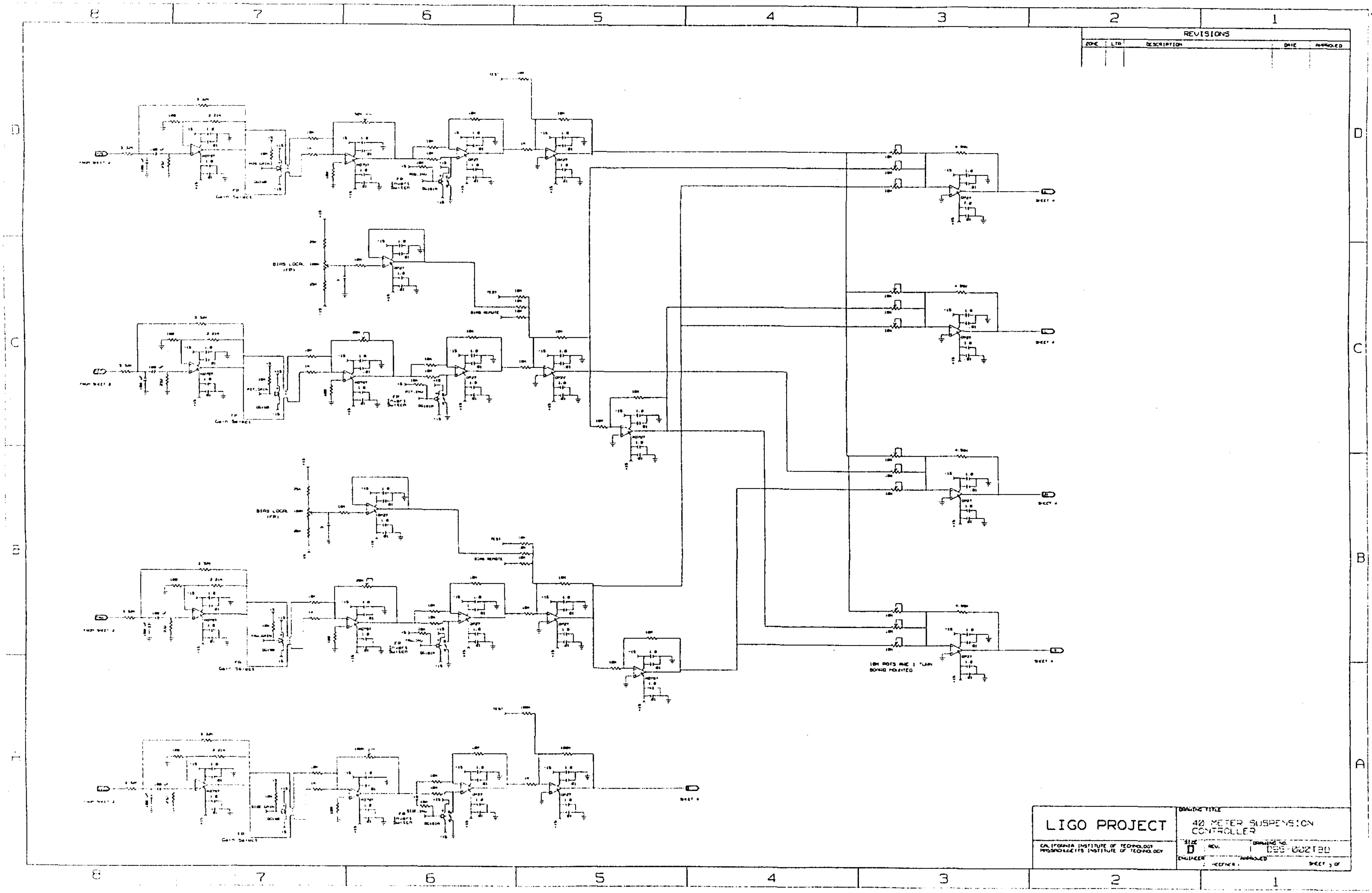
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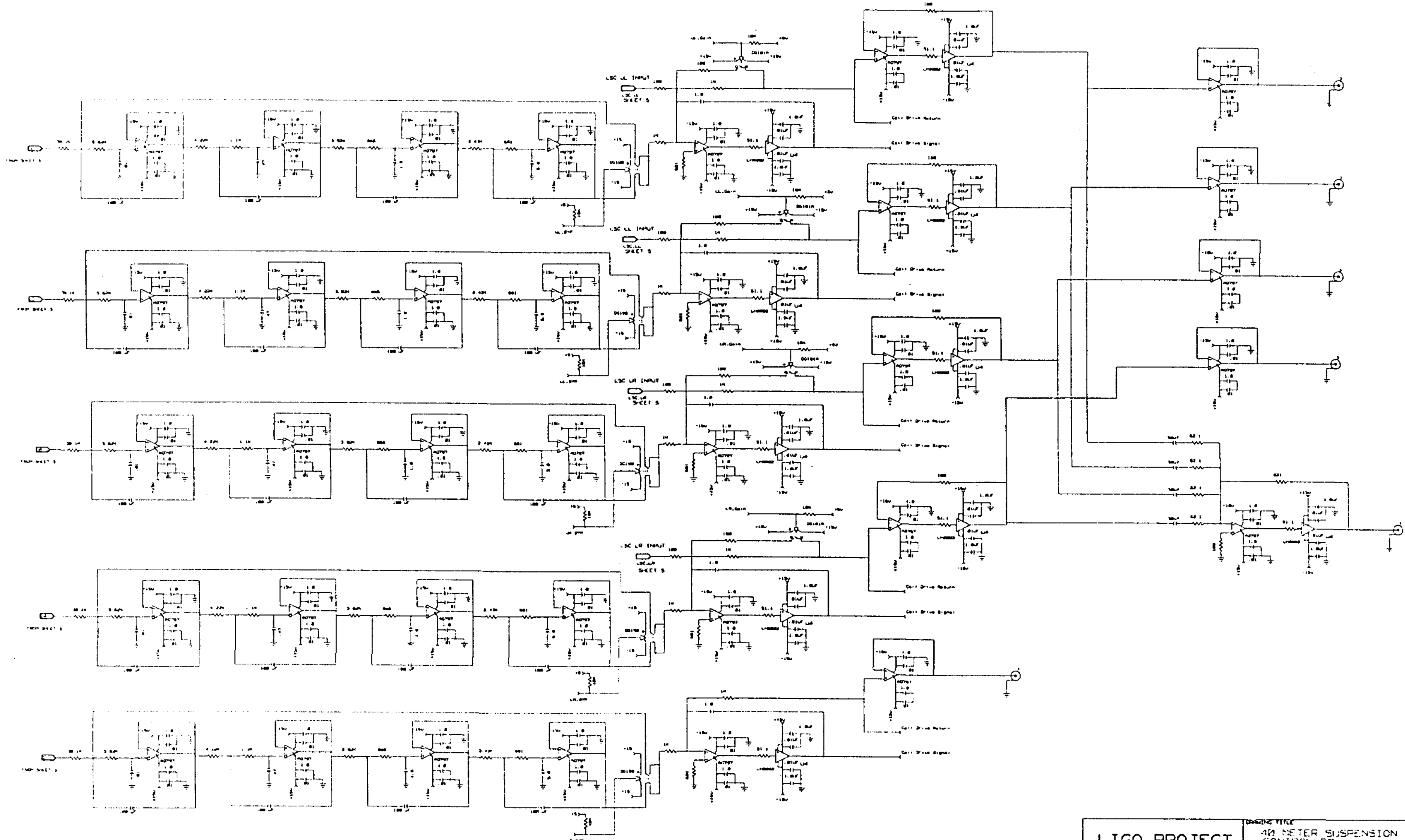


REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED

LIGO PROJECT

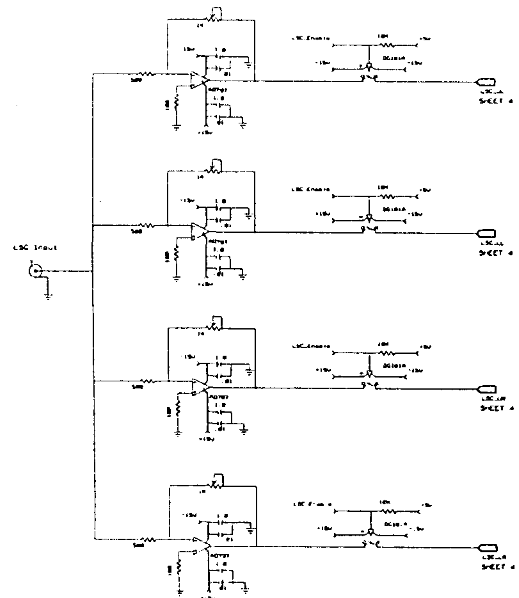
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DRAWING TITLE: 40 METER SUSPENSION CONTROLLER

SIZE: D | REV. | DRAWING NO. D95-0201B0

ENGINEER: J. HEEFNER | APPROVED | SHEET 4 OF

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED



LIGO PROJECT

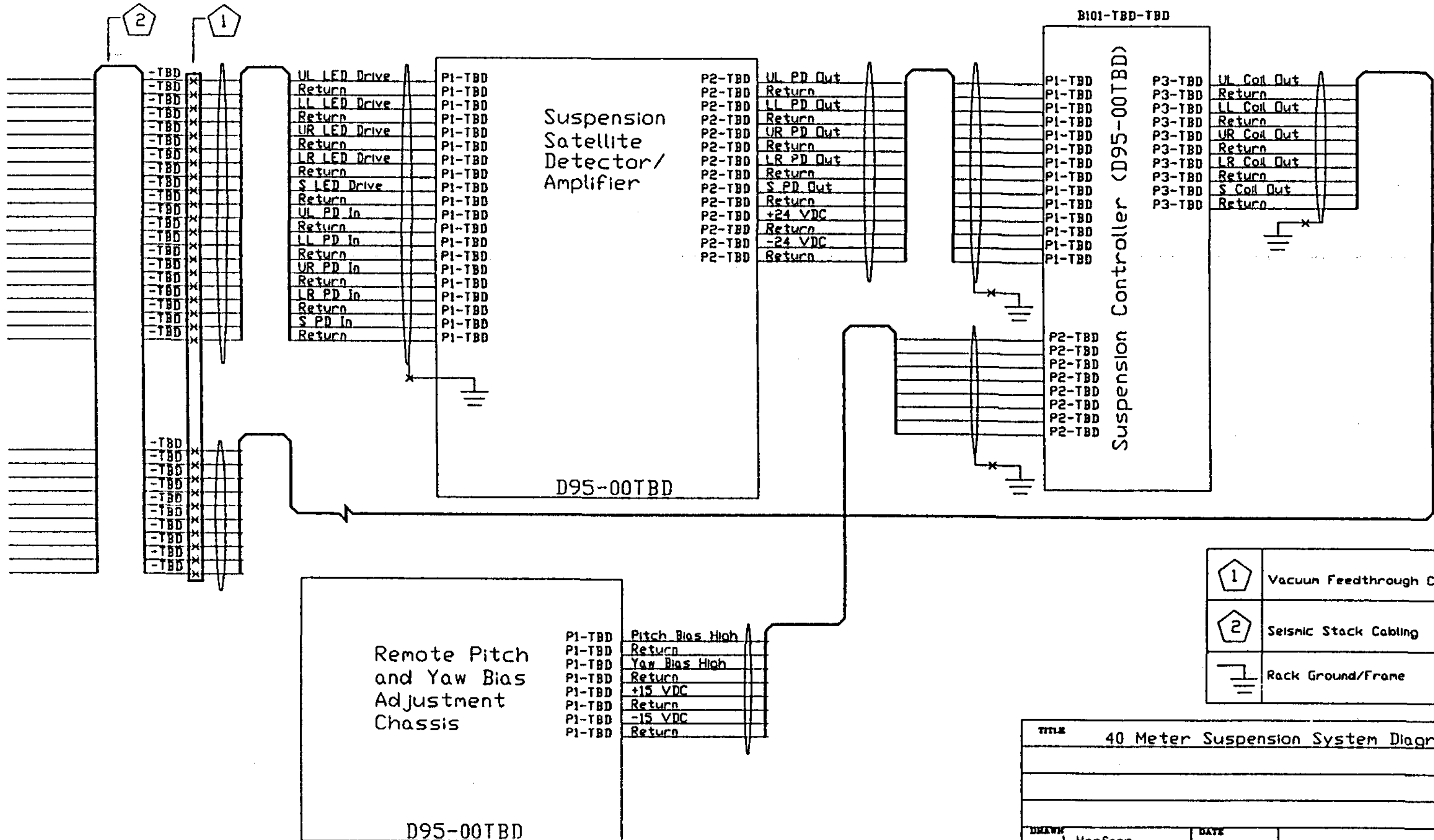
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DRAWING TITLE
40 METER SUSPENSION CONTROLLER

SIZE	REV.	DRAWING NO.
D		DSS-C20TBD

ENGINEER	APPROVED	SHEET
J. HEEFNER		SHEET 1 OF

REV.	Description	Date	Appr.



1	Vacuum Feedthrough Connector
2	Seismic Stack Cabling
⏚	Rack Ground/Frame

TITLE	40 Meter Suspension System Diagram				
DRAWN J. Heefner	DATE	LIGO Laser Interferometer Gravitational-Wave Observatory California Institute of Technology Massachusetts Institute of Technology			
CHECKED	DATE				
APPROVED	DATE				
ENGINEER J. Heefner		FILE NUMBER	SIZE D	DRAWING NUMBER D95-00TBD	REV. A
SCALE:	SHOWN ON			SHEET 1 of 1	