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Beam Splitter and Recycling Mirror Suspension Controller Design Requirements

J. Heefner

Distribution of this draft:

R. Abbott, D. Durance, S. Kawamura, J. Logan, T. Lyons, J. Mason, M. Rakhmanov, R. Spero

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

Abstract

This technical note describes the design requirements for the 40 Meter Interferometer recycling mirror and beam splitter suspension controller electronics. The design of the suspension controller for both types of optics will be the same and is a precursor to the design of the LIGO small optics suspension controller electronics.

1 INTRODUCTION

1.1. Purpose

The purpose of this is to describe and document the design requirements for the recycling mirror and beam splitter suspension controller electronics to be designed and installed as part of the recycled interferometer configuration.

1.2. Scope

This document covers the design and performance requirements for all electronics to be used for the suspension controls of the recycling mirror and beam splitter to be used in the recycled interferometer configuration of the 40 meter interferometer.

1.3. Definitions

Suspension Controller- In the context of this document the suspension controller refers to the suspension controller module that will be used to control both the beam splitter and the recycling mirror.

1.4. Acronyms

- ASC- Alignment Sensing and Control
- CDS- Control and Data System
- LED- Light Emitting Diode
- LIGO- Laser Interferometer Gravitational-wave Observatory
- LL- Lower left suspension coil or photodiode
- LR- Lower right suspension coil or photodiode
- LSC- Length Sensing and Control
- MTBF- Mean Time Between Failure
- MTTR- Mean Time To Repair
- PD- Photodiode
- PIT- Pitch of optic being controlled
- POS- Longitudinal position of optic being controlled
- S- Lateral position of optic being controlled
- TBD- To Be Determined
- UL- Upper left suspension coil or photodiode
- UR- Upper right suspension coil or photodiode
- YAW- Yaw of optic being controlled

1.5. Applicable Documents

1.5.1. LIGO Documents

- LIGO T950011: Suspension Design Requirments
- LIGO T950058: Design Report of the 40M Test Mass Suspension Prototype

1.5.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Product Perspective

The suspension controller electronics described in this document specify the servo electronics, controls and monitors that form the beam splitter and recycling mirror suspension control systems for the recycled interferometer configuration that will be installed on the 40 meter interferometer on the Caltech campus.

A block diagram of the suspension control electronics is shown in the figure below. Devices covered by this requirements document are shown within the shaded region.

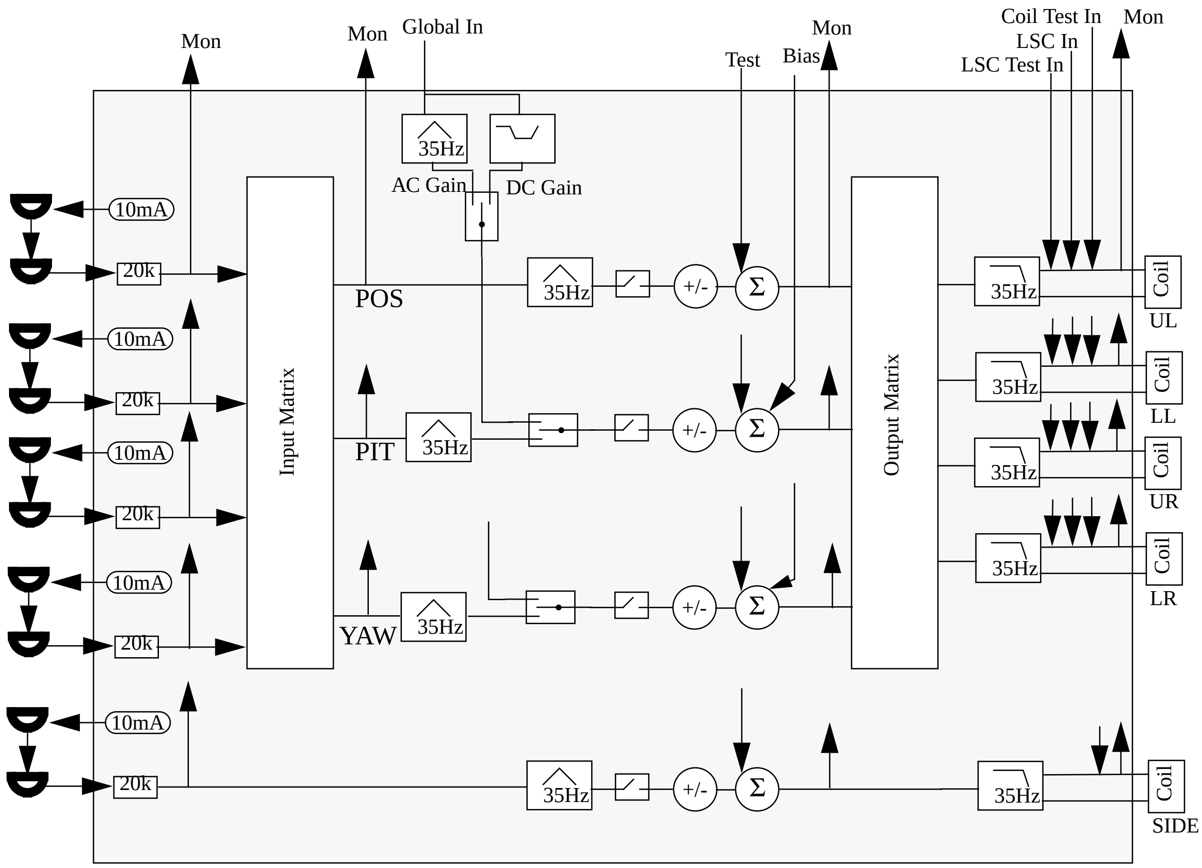


Figure 1: Schematic diagram of the electronic system of the suspension control.

2.2. Product Functions

The suspension controller electronics can be separated into two functional components: the photodiode/LED electronics and the suspension controller itself. The function of each is described below.

2.2.1. Photodiode/LED Electronics

The photodiode/LED electronics provide for the local read back of optic orientation that is used to control in the local control mode described in the sections that follow. Each coil has associated with it a photodiode and LED pair as shown in Figure 1. The function of the electronics is to provide a constant current source to the LED and convert the photodiode current to a voltage for use by the suspension controller.

2.2.2. Suspension Controller

The function of the suspension controller is to provide a damped optic for use in the interferometer. In addition the suspension controller provides a means by which other systems such as ASC and LSC can control the pitch, yaw, and longitudinal position of the optic.

2.3. General Constraints

2.3.1. Equipment Locations

Due to space limitations and the configuration of the 40 meter interferometer, the electronics for the suspension controllers must be confined to a single 19 inch rack located near the east vertex chamber of the interferometer. This rack is to be shared with the recycling electronics. These constraints only apply to the rack mounted components and not to any line drivers or preamplifiers that may be used to boost signals closer to the devices being controlled or monitored.

Permanent or fixed operator consoles will be located in the control room and work area adjacent to the 40 meter interferometer.

2.3.2. Vacuum Cabling and Devices Internal to the Vacuum Chamber

Vacuum cabling, connectors, feedthroughs and devices internal to the vacuum chamber must adhere to the vacuum qualification, cleaning and maintenance procedures that have been established for the 40 meter interferometer.

2.3.3. Computer Networks and Network Equipment

The recycled interferometer controls, including suspension controls, shall utilize the existing CDS network and networking equipment located in the 40 meter laboratory. Connection of devices within the laboratory or the control area adjacent to the laboratory shall be via 10baseT connections. Existing cabling and network hubs utilize category 5 cabling with RJ-45 connectors.

2.4. Assumptions and Dependencies

3 REQUIREMENTS

3.1. Characteristics

3.1.1. Performance Characteristics

3.1.1.1 Photodiode and LED Electronics

3.1.1.1.1 LED Drive Current

The electronics shall provide a constant current of 10 mA to each of the LEDs. This current shall be accurate to +/- 1% and be stable to better than TBD ppm over the full temperature range specified in the sections below.

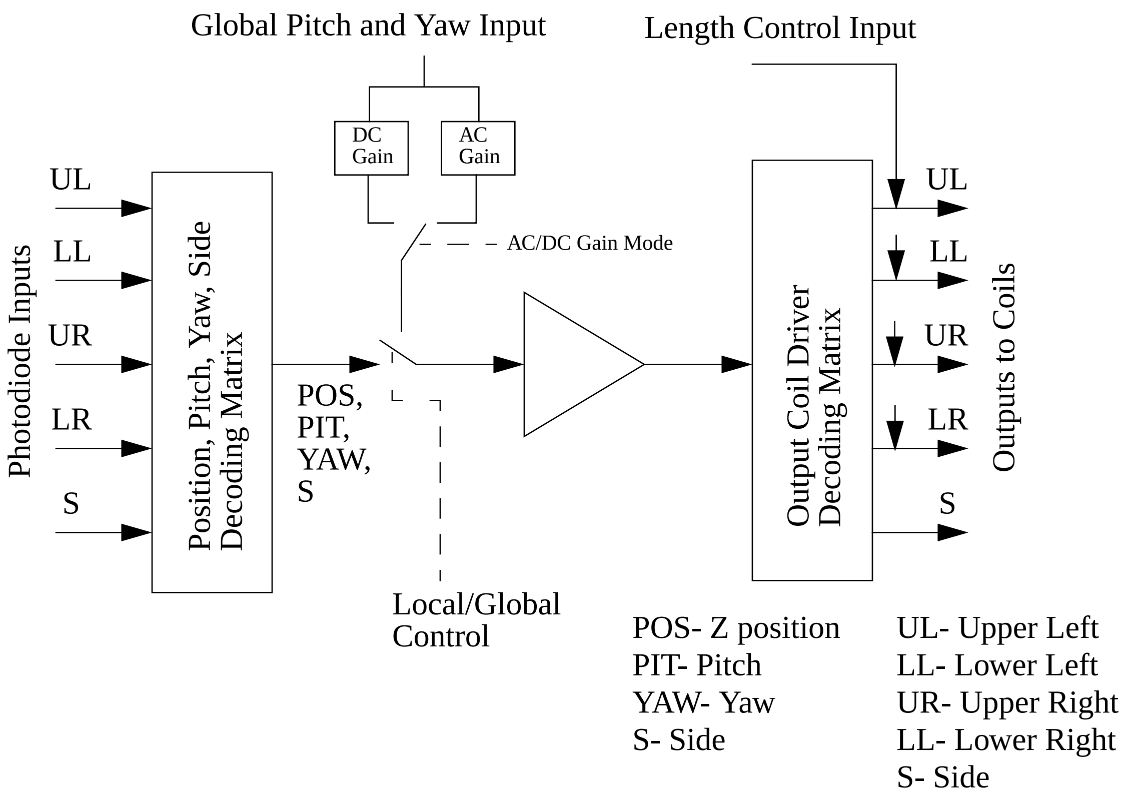
Output referred current noise shall be less than $(100\,pA)/(\sqrt{Hz})$ for frequencies greater than 0.1 Hz.

3.1.1.1.2 Photodiode Current to Voltage Conversion

The transimpedance of each photodiode pre-amplifier (5 total) shall be 20 Kohms, +/- 1%. The output referred voltage noise shall be better than $(10nV)/(\sqrt{Hz})$ for frequencies greater than 10 Hz.

3.1.1.2 Suspension Controller Transfer Functions

A block diagram of the suspension controller is shown in the figure below.



As can be seen from the figure, there are three signal paths:

- Photodiode input to coil driver output
- Global pitch and yaw to coil driver output
- Length control input to coil driver output

The nominal calculation of POS, PIT and YAW shall be as follows:

- POS= UL+LL+UR+LR
- PIT=(UL+UR)-(LL+LR)
- YAW=(UL+LL)-(UR+LR)

The design shall such that the "balance" for each channel may be trimmed by the operator. For example:

$$POS = K1 \bullet UL + K2 \bullet LL + K3 \bullet UR + K4 \bullet LR$$

$$PIT = K5 \bullet UL - K6 \bullet LL + K7 \bullet UR - K8 \bullet LR$$

$$YAW = K9 \bullet UL + K10 \bullet LL - K11 \bullet UR - K12 \bullet LR$$

where K1 through K12 are nominally equal to unity, and are adjustable from 0.75 to 1.25 in step sizes of 0.5% minimum.

The nominal calculation of outputs UL, LL, UR, LR from POS, PIT and Yaw are as follows:

- UL=POS+PIT+YAW
- LL=POS-PIT+YAW
- UR=POS+PIT-YAW
- LR=POS-PIT-YAW

The design shall such that the “balance” for each output channel may be trimmed by the operator. For example:

$$UL = C1 \bullet POS + C2 \bullet PIT + C3 \bullet YAW$$

$$LL = C4 \bullet POS - C5 \bullet PIT + C6 \bullet YAW$$

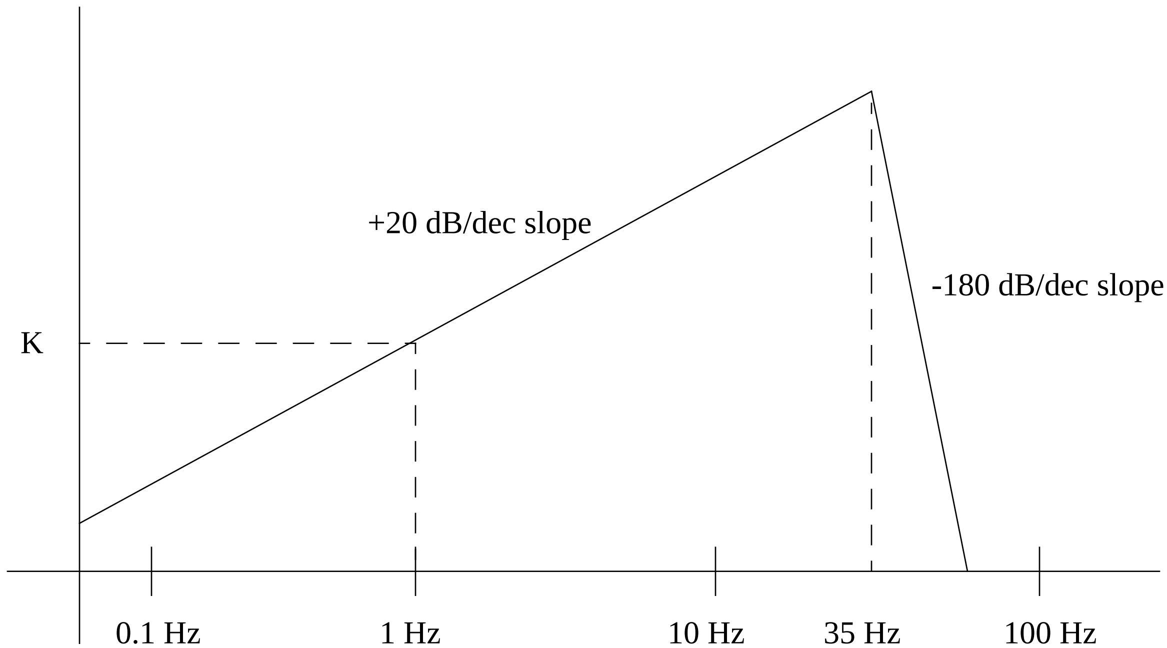
$$UR = C7 \bullet POS + C8 \bullet PIT - C9 \bullet YAW$$

$$UL = C10 \bullet POS - C11 \bullet PIT - C12 \bullet YAW$$

where C1 through C12 are nominally equal to unity, and are adjustable from 0.75 to 1.25 in step sizes of 0.5% minimum.

3.1.1.2.1 POS, PIT YAW Input to Coil Driver Output Transfer Function (Local Control)

The transfer function from each photodiode input to each coil driver output shall be a 10 pole, 1 dB ripple, 35 Hz chebychev low pass filter with an additional zero placed at DC. The nominal gain of the filter at 1 Hz shall be as shown below. The figure below shows a bode plot of the transfer function.



K= 26 dB for PIT
K= 26 dB for YAW
K= 34 dB for POS
K= 60 dB for S

Figure 2: Local Control Transfer Function

3.1.1.2.2 Global Pitch and Yaw Inputs to Coil Driver Outputs (Global Control)

The global pitch and yaw shall have two modes of operation: DC gain mode and AC gain mode. The transfer functions for each mode are shown in the figure below. The response for each above

1 Hz shall be identical to the response described for the Photodiode input to coil driver output described above.

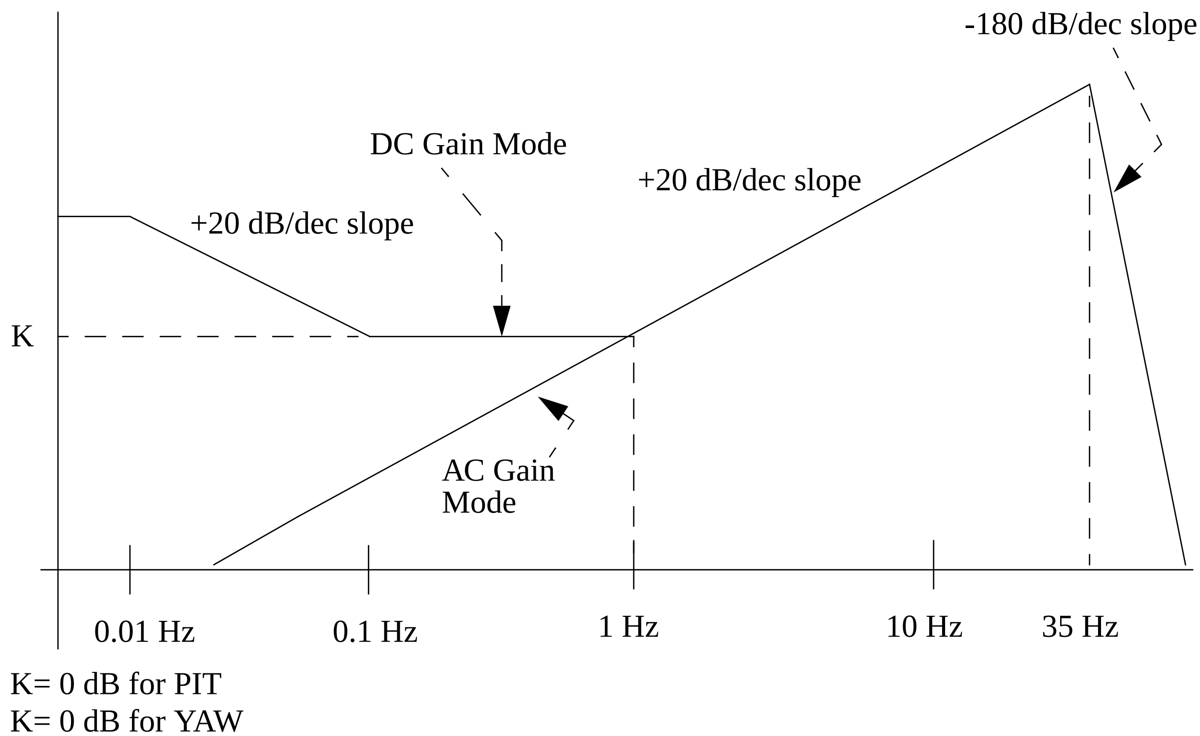


Figure 3: Global Control Transfer Function

In the AC gain mode of operation, the transfer function is the same as the response of the filter described in section 3.1.1.1.1.

In the DC gain mode the zero at DC is not present and a pole at 0.01 Hz and zeros at 0.1 and 1 Hz have been added. The 35 Hz low pass filter response is the same 10 pole, 1 dB ripple chebychev response described in section 3.1.1.1.1.

3.1.1.2.3 Length Control Input to Coil Driver Output Transfer Function

The length control input provides a means for an external servo loop to adjust the longitudinal position of the optic that is being controlled. The transfer function from the LSC input to each coil driver output (UL, LL, UR, LR only) shall be 8 mA/V with a bandwidth greater than 1 KHz.The input impedance of the input shall be 125 ohms +/- 5 ohm.

The design shall such that the gain from the LSC input to each output channel may be trimmed by the operator. For example:

$$UL_{LSC} = X1 \bullet LSC_{in}$$

$$LL_{LSC} = X2 \bullet LSC_{in}$$

$$UR_{LSC} = X3 \bullet LSC_{in}$$

$$LR_{LSC} = X4 \bullet LSC_{in}$$

where X1 through X4 are nominally equal to 8mA/V, and is adjustable +/-25% in step sizes of 0.5% minimum.

The length control input shall have two modes of operation that shall be selectable by the operator. The modes are defined as:

- Acquisition mode: Maximum drive current to the coil shall be limited to +/- 30 mA.
- Locked mode: Maximum drive current to the coil shall be limited to +/- 3 mA.
- Off Mode: LSC Input Disabled

3.1.1.3 Coil Drive Output Configuration

The coil driver output shall be configured such that the coil is in the feedback loop of the output operational amplifier (ref. schematic D95-00166). This configuration has been shown through testing to provide the best performance from the standpoint of noise and stability.

Output coil drive and LSC monitors shall be as shown in schematic D95-00166.

3.1.1.4 Input and Output Noise

The output referred noise current of the suspension controller shall be less than $(6pA)/(\sqrt{Hz})$ at 100 Hz and all line related spikes shall be less than TBDnA rms.

The output noise at frequencies less than 100 Hz shall be dominated by the Johnson noise of the 20 Kohm resistor that is used as a current to voltage converter on the photodiode output, i.e. input referred noise shall be less than $(17nV)/(\sqrt{Hz})$ at frequencies less than 100 Hz.

3.1.1.5 Indicators, Monitors and Controls

3.1.1.5.1 Gain Adjustment and Inversion

The gain of the transfer functions shall be adjustable by the operator. This gain adjustment shall be +20 and -40 dB from the nominal gains stated above in 1 dB steps.

A mechanism shall be provided such that the operator can invert each of the responses described in section 3.1.1.1 above.

3.1.1.5.2 Local and Global Pitch and Yaw Control

The operator shall be able to select between local or global (AC or DC mode) pitch and yaw control of the optic. The transfer from local to global control or vis versa shall be “bumpless” and not cause the interferometer to lose lock. The changing of modes from local to global AC or global DC shall not cause any portion of the amplifier circuit to saturate and shall be accomplished with 10 seconds of operator initiation.

3.1.1.5.3 Low Pass Filter Bypass

A mechanism shall be provided such that the operator may bypass the last 8 poles of the chebychev low pass filter response for each output coil.

3.1.1.5.4 Monitors

Monitors, both front panel and computer, shall be provided for the following:

- Output coil currents
- Local pitch, yaw and position
- Photodiode output voltages
- LSC sum monitor

The bandwidth of front panel monitors shall be greater than 1 KHz. Computer monitors available to the operator display at a maximum 10 Hz rate and minimum 12 bit resolution.

3.1.1.6 Test Inputs, Outputs and Functions

Test inputs, monitors and controls shall be provided such that the closed loop transfer function of the suspension controller servo can be measured while the servo loop is closed.

A means of opening the servo loop and injecting a test signal into suspension controller shall be provided. Opening of the servo loop shall be accomplished without removing cables or disconnecting devices.

The position of each test input and monitor shall be as shown in figure 1.

An LSC Test Input shall be incorporated into the design.

All test inputs shall have the capability of being disabled by the operator.

3.1.2. Physical Characteristics

3.1.2.1 Electronic Equipment Housings

To the extent possible and reasonable the following shall be applied to the suspension controller electronics.

- All equipment shall be housed in standard 19 inch racks.
- Standard 6U VME enclosures with VME, dummy or split backplanes shall be used, as appropriate, for custom and commercial modules.
- Custom electronics modules shall be 6U VME format and shall follow the design standards imposed by the LIGO CDS group.

3.1.2.2 Cabling and Connections

All cabling and connection of electronics modules and devices shall be in accordance with standard LIGO CDS grounding and shielding policies.

All field cabling shall be run in the cable trays that are provided below the vacuum chamber.

3.1.3. Interface Definitions

3.1.3.1 Interfaces to other 40 meter subsystems

3.1.3.1.1 Mechanical Interfaces

The following table summarizes the mechanical interfaces to other 40 meter subsystems.

Table 1: Mechanical Interfaces to Other 40 Meter Subsystems

Interface	*40 meter Subsystem*	*Characteristics*
Vacuum cabling mount to seismic isolation stacks	seismic isolation	TBD
Vacuum feedthrough connector	vacuum chamber	TBD

3.1.3.1.2 Electrical Interfaces

The following table summarizes the electrical interfaces to other 40 meter subsystems.

Table 2: Electrical Interfaces to Other 40 Meter Subsystems

Interface	*40 meter Subsystem*	*Characteristics*
Fast Z input to Recycling Mirror Suspension Controller	Recycling Mirror Servo electronics	Input Impedance: 125 ohms Transfer Function: 8mA/V Connector: TBD
Fast Z input to Beam Splitter Suspension Controller	Beam Splitter Servo electronics	Input Impedance: 125 ohms Transfer Function: 8mA/V Connector: TBD
UL, LL, UR, LR, S coils	Suspension system	Connector: TBD
UL, LL, UR, LR, S Photodiodes	Suspension system	Connector: TBD
UL, LL, UR, LR, S LEDs	Suspension system	Connector: TBD

3.1.3.1.3 Optical Interfaces

N/A

3.1.3.1.4 Stay Clear Zones

3.1.3.2 Interfaces external to 40 meter subsystems

3.1.3.2.1 Mechanical Interfaces

3.1.3.2.2 Electrical Interfaces

The following table summarizes the electrical interfaces to systems external to the 40 meter interferometer.

Table 3: Electrical Interfaces to non- 40 Meter Subsystems

Interface	*System*	*Characteristics*
Rack AC Power	Laboratory AC Power System	Voltage: 115 VAC, +TBD, -TBD Current: 16 A max. Frequency: 60 Hz
Operator Console AC Power	Laboratory AC Power System	Voltage: 115 VAC, +TBD, -TBD Current: 16 A max. Frequency: 60 Hz

3.1.3.2.3 Stay Clear Zones

3.1.4. Reliability

The Mean Time Between Failure (MTBF) for components shall be greater than TBD.

3.1.5. Maintainability

The Mean Time To Repair (MTTR) for components shall be less than TBD

3.1.6. Environmental Conditions

The suspension controller electronics shall meet all performance requirements when exposed to all specified natural and induced environments.

3.1.6.1 Natural Environment

3.1.6.1.1 Temperature and Humidity

Table 4: Environmental Performance Characteristics

Operating	*Non-operating (storage)*	*Transport*
+0 C to +50 C, 0-90%RH	-40 C to +70 C, 0-90% RH	-40 C to +70 C, 0-90% RH

3.1.6.1.2 Atmospheric Pressure

The suspension controller electronics design must accommodate atmospheric pressure changes from a maximum of 15.2 psia to a minimum of 14.2 psia.

3.1.6.1.3 Seismic Disturbance

N/A

3.1.6.2 Induced Environment

3.1.6.2.1 Electromagnetic Radiation

The suspension controller electronics shall not degrade due to electromagnetic emissions as specified by IEEE C95.1-1991.

The suspension controller electronics shall not produce electromagnetic emissions greater than TBD.

3.1.6.2.2 Acoustic

Suspension controller electronics and associated control components shall be designed to produce the lowest levels of acoustic noise as possible and practical. In any event, acoustic noise levels greater than TBD will not be produced.

3.1.6.2.3 Mechanical Vibration

Suspension controller electronics and associated control components shall not produce mechanical vibrations greater than TBD.

3.1.7. Transportability

All items shall be transportable by commercial carrier without degradation in performance. As necessary, provisions shall be made for measuring and controlling environmental conditions (temperature and accelerations) during transport and handling. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage. All containers shall be movable for forklift. All items over 100 lbs. which must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

3.2. Design and Construction

3.2.1. Materials and Processes

Such items as units of measure to be used (English, Metric) should be listed and any other general items, such as standard polishing procedures and processes.

3.2.1.1 Finishes

- Ambient Environment: Surface-to-surface contact between dissimilar metals shall be controlled in accordance with the best available practices for corrosion prevention and control.
- *External surfaces: External surfaces requiring protection shall be painted purple or otherwise protected in a manner to be approved.*

3.2.1.2 Materials

All suspension controller electronics and equipment to be placed inside the 40 meter vacuum chamber shall be in accordance with the LIGO list of approved vacuum materials. LIGO document number TBD.

3.2.1.3 Processes

All suspension controller electronics and equipment to be placed inside the 40 meter vacuum chamber shall be cleaned in accordance with the LIGO 40 meter vacuum cleaning standards. LIGO document number TBD.

3.2.2. Component Naming

All components shall identified using the LIGO Detector Naming Convention (document TBD). This shall include identification physically on components, in all drawings and in all related documentation.

3.2.3. Workmanship

All details of workmanship shall be of the highest grade appropriate to the methods and level of fabrication and consistent with the requirements specified herein. There shall be no evidence of poor workmanship that would make the components unsuitable for the purpose intended. All electronic circuits, modules and wiring shall be consistent with good engineering practice and fabricated to the best commercial standards.

3.2.4. Interchangeability

The suspension controller electronics and equipment shall be designed to maximize interchangeability and replaceability of mating components. Using the Line Replaceable Unit (LRU) concept, the designs shall be such that mating assemblies may be exchanged without selection for fit or performance and without modification to the section, the unit being replaced or adjacent equipment. Mature, performance proven, standard, commercially available equipment shall not be modified unless it impacts safety.

3.2.5. Safety

This item shall meet all applicable NSF and other Federal safety regulations, plus those applicable State, Local and LIGO safety requirements. A hazard/risk analysis shall be conducted in accordance with guidelines set forth in the LIGO Project System Safety Management Plan LIGO-M950046-F, section 3.3.2.

3.2.6. Human Engineering

The suspension controller electronics and associated components shall be designed and laid out in a manner consistent with applicable standard human engineering practices. Particular attention shall be paid to layouts of operator consoles/stations, work space and environmental conditions.

3.3. Documentation

3.3.1. Specifications

The following specifications shall be developed in the course of the design:

- TBD

3.3.2. Design Documents

The following design documents shall be provided:

- Suspension Controller Hardware Design and Description
- Suspension Controller Software Design Document

3.3.3. Engineering Drawings and Associated Lists

Engineering drawings, schematics, wire lists and cable routing lists shall be produced for the recycling electronics. To the greatest extent possible and practical, electronic copies shall be maintained and available on-line. All drawings shall be formatted according to LIGO standards.

3.3.4. Technical Manuals and Procedures

3.3.4.1 Procedures

Procedures shall be provided for, at minimum,

- *Initial installation and setup of equipment*
- *Normal operation of equipment*
- *Normal and/or preventative maintenance*
- *Troubleshooting guide for any anticipated potential malfunctions*

3.3.4.2 Manuals

The following manuals shall be provided:

- All manuals provided by commercial vendors for recycling components

- Manuals for all CDS produced electronics and software.

3.3.5. Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering system LIGO document TBD

3.3.6. Test Plans and Procedures

All test plans and procedures shall be developed in accordance with the LIGO Test Plan Guidelines, LIGO document TBD.

3.4. Logistics

The design shall include a list of all recommended spare parts and special test equipment required.

3.5. Precedence

In the event of conflicts between this requirement document and other LIGO documents, this document shall take precedence.

3.6. Qualification

Qualification of various components and systems shall be in accordance with section 4 of this document.

4 QUALITY ASSURANCE PROVISIONS

4.1. General

4.1.1. Responsibility for Tests

The CDS group shall be responsible for performing all tests, including development of appropriate test plans and procedures.

4.1.2. Special Tests

4.1.2.1 Engineering Tests

TBD

4.1.2.2 Reliability Testing

Reliability evaluation/development tests shall be conducted on items with limited reliability history that will have a significant impact upon the operational availability of the system.

4.1.3. Configuration Management

Configuration control of specifications and designs shall be in accordance with the LIGO Detector Implementation Plan.

4.2. Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis, demonstration, similarity, test or a combination thereof per the Verification Matrix, Appendix 1 (See example in Appendix). Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures. Verification of compliance to the requirements of this and subsequent specifications may be accomplished by the following methods or combination of methods:

4.2.1. Inspections

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

4.2.2. Analysis

Analysis may be used for determination of qualitative and quantitative properties and performance of an item by study, calculation and modeling.

4.2.3. Demonstration

Demonstration may be used for determination of qualitative properties and performance of an item and is accomplished by observation. Verification of an item by this method would be accomplished by using the item for the designated design purpose and would require no special test for final proof of performance.

4.2.4. Similarity

Similarity analysis may be used in lieu of tests when a determination can be made that an item is similar or identical in design to another item that has been previously certified to equivalent or more stringent criteria. Qualification by similarity is subject to Detector management approval.

4.2.5. Test

Test may be used for the determination of quantitative properties and performance of an item by technical means, such as, the use of external resources, such as voltmeters, recorders, and any test equipment necessary for measuring performance. Test equipment used shall be calibrated to the *manufacture's specifications and shall have a calibration sticker showing the current calibration status.*

5 PREPARATION FOR DELIVERY

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

5.1. Preparation

Equipment shall be appropriately prepared. For example, vacuum components shall be prepared to prevent contamination.

5.2. Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage.

5.3. Marking

Appropriate identification of the product, both on packages and shipping containers; all markings necessary for delivery and for storage, if applicable; all markings required by regulations, statutes, and common carriers; and all markings necessary for safety and safe delivery shall be provided.

6 NOTES

N/A

APPENDIX 1 QUALITY CONFORMANCE INSPECTIONS

The following table shows the methods of testing that will be used for verification of quality conformance.

Table 5: Quality Conformance Inspections

Paragraph	*Title*	*I*	*A*	*D*	*S*	*T*