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Integrated System of Sensors and Actuators for the Advanced LIGO Mirror Suspensions: A Review

Sudarshan S Haritha s

UG Student, Dept. of ECE, B.M.S College of Engineering, Bangalore, Karnataka, India

ABSTRACT:The Laser Interferometer Gravitational Wave Observatory (LIGO) consists of two widely separated laser interferometers each 4Km long, designed to detect gravitational waves from distant astrophysical sources in the frequency range from 10Hz to 10 kHz. The presented paper is a review on the integrated system sensors, actuators and related read-out and drive electronics developed for the control of advanced LIGO mirror suspensions. It consist of an elaborate description regarding its working and hardware specification on three instruments namely BOSEM (Birmingham optical sensor and electromagnetic actuator), satellite boxes (BOSEM readout and interface electronics) and the coil-driver units.

KEYWORDS: Gravitational waves, interferometers, BOSEM, shadow sensor, satellite boxes, coil-driver units.

I.INTRODUCTION

Gravitational waves:

In Einstein's General Theory of Relativity gravity is treated as a phenomenon resulting from a curvature of spacetime. This curvature is caused by the presence of mass. As objects with mass move around in spacetime the curvature changes to reflect the changed locations of those objects. In certain circumstances, accelerating objects generate changes in the curvature which propagate outwards at the speed of light in a wave like manner this propagating phenomenon is known as gravitational waves.

As gravitational waves passes an observer, the distortion of spacetime by the effects of strain would be observed. Distances between the objects would increase and decrease rhythmically as the wave passes, at a frequency corresponding to that of the wave.
The sources of gravitational waves can be classified into 4 categories

- Short lived and well defined for which coalescence of a compact binary system is a canonical example.
- Short lived and a priori poorly known for which a supernova is a canonical example.
- Continuous and well defined for which a spinning neutron star is a canonical example.
- Long lived and stochastic for which primordial gravitational waves from big bang is an example.

Detection principles:

Until the mid-20th century there remained some question as to whether or not gravitational waves were truly predicted by general relativity. It was not obvious that what appeared to be a phenomenon could be explained away as an artifact of coordinate/gauge transformations. The reality of gravitational wave prediction was confirmed by the realization that energy could be extracted from these waves i.e. it was possible in principle to build a detector that could register their passage. The earliest manmade gravitational detectors were pioneered by Joe Weber from the University of Maryland. He designed resonant bar detectors and implemented them, he also reported anomalies attributed to gravitational waves, such as coincident transients in geographically separated pairs of bars, but subsequent experiments with comparable or more sensitive instruments failed to confirm the reported detections.

Gravitational-wave interferometers take a different approach to detection from that of resonant bars. Setting aside enhancements to be discussed below, a simple right-angle Michelson laser interferometer, as shown in the cartoon in figure1 is a natural gravitational wave detector. For example, a linearly polarized wave impinging normally on the

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interferometer with its polarization axis aligned with the arms will alternately stretch one arm while contracting the other. The detection is based on the phase difference between the light returning from each arm, and that phase difference increases with time, following the passage of the gravitational wave. The red-shifted light simply takes longer to complete its round-trip in the arm than the blue-shifted light. Hence even an idealized, simple gravitational-wave interferometer has a finite and frequency-dependent response time.

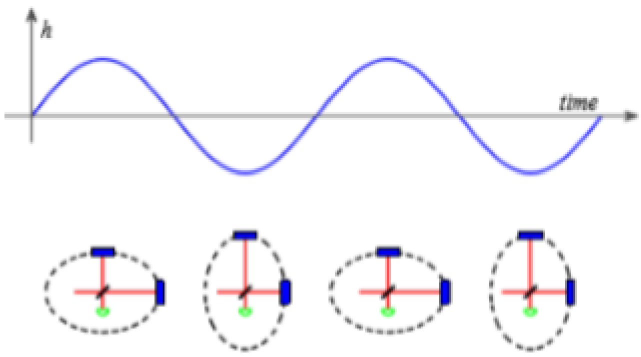

Fig1: Cartoon illustration of the effect of a gravitational wave on the arms of a Michelson interferometer, where the readout photodiode is denoted by the green semi-circle.

The basic idea for a gravitational wave interferometer was first written down by Gertsenshtein and Pustovoit in 1962. Weber's group developed this idea further into the first gravitational wave interferometer prototype built by Weber graduate Robert Forward at Hughes Aircraft Research Lab. It was early work carried out in parallel by Rai Weiss, however, that laid the groundwork for present-day gravitational wave interferometers. As discussed furtherbelow, it became appreciated quickly that laser interferometers had the potential to surpass bar detectors in sensitivity, and there was rapid development of ideas and technology. Subsequent improvements included (among many others) using Fabry-Perot cavities for the interferometer arms to increase the time of exposure of the laser light to the gravitational wave, introduction of a "recycling" mirror between the laser and beam-splitter, to increase effective laser power, and introduction of another mirror between the beam splitter and photodetector to allow tuning of the interferometer's frequency response. This paper is an overview of the design of integrated system of sensors and actuators within the Advanced LIGO suspensions.

II.SENSORS AND ACTUATORS FOR THE ADVANCED LIGO

The integrated systems of sensors and actuators developed for the control of advanced LIGO mirror suspensions consist of three instruments

- BOSEM it consist of optical position sensor and electromagnetic actuator.
- Satellite boxes, electronic interfaces for the BOSEM displacement sensor.
- Coil driver unit, electric current drivers for BOSEM actuator.

The working principle of integrated circuit BOSEM readout and actuation of suspension is shown in figure2. The motion of the suspended test mass is sensed by BOSEM, a corresponding signal is generated and is amplified and filtered by the satellite boxes and sent to the main digital control system. Here the main signal is processed and purposely optimised to be then fed back through the coil driver amplifier to the BOSEM coil, to eventually actuating the suspended mass.

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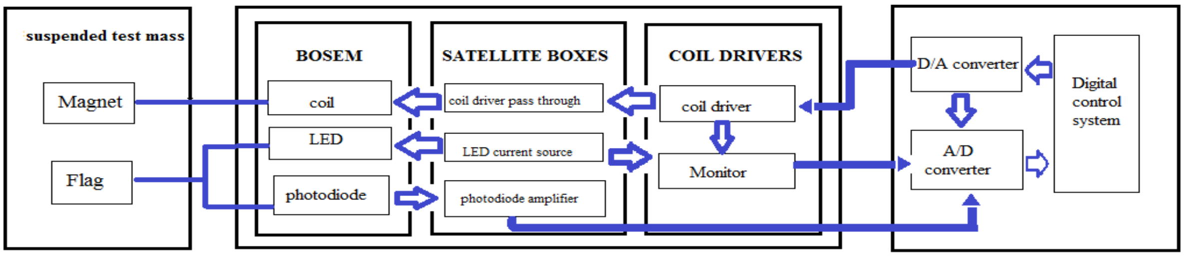

Fig2: Schematic of the working principle of the integrated system of BOSEMS, satellite boxes and coil-drivers.

1. BOSEM:

BOSEM is a compact, ultra-high vacuum (UHV) compatible, non-contact, low noise position sensor with electromagnetic actuator. The working principle of BOSEM is based on the original principle of Shoemaker et al [10]. BOSEM consist of several interconnected subsystems.

- Optical sensor.
- Electromagnetic actuator.
- Mounting and adjustment.
- Electrical interconnect.
- Magnet and flag.

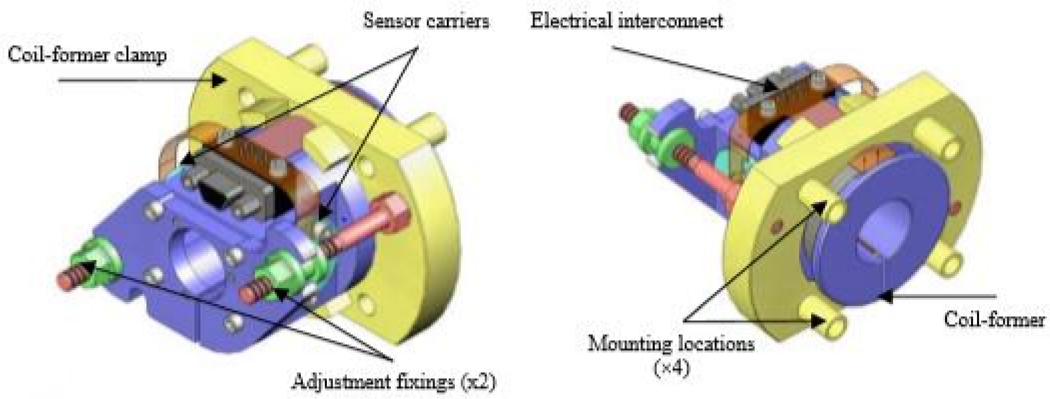

Fig3: 3D CAD model of BOSEM assembly. (Left) Rear isometric view. (Right) Front isometric view.

The Advanced LIGO interferometers comprise of several different types of optical components, some of which are required to operate within a low noise environment. The most sensitive optics, i.e. the 40 kg fussed silica test masses, must be held in place to within 10^{-14} m by a combined seismic isolation and suspension system. An investigation was conducted by Strain[11] to determine the optimal approach to sensing and actuation, assuming a modest amount of eddy current damping. This approach was successfully reviewed [12] and eventually resulted in the sensor requirements being relaxed, with the final sensitivity and operating range requirements placed on the sensor as presented in Table1.

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Specification	Frequency Band	
Worst Case Noise	1 Hz to 10 Hz 3×10^{-10} m/√Hz	10 Hz to 20 Hz 1×10^{-10} m/√Hz
Specification	Displacement (peak to peak)	
Operating Range	Minimum 0.35 mm	Target 0.70 mm

Table1: Final sensor requirements.

1.1 OPTICAL SENSOR

Geometric sensors can be used to measure the position of the object they commonly involve the use of PSD (position sensitive devices) or split photodiodes the configuration of shadow sensor is shown in figure4. It consist of two cylindrical lenses to focus a beam from a collimated light source, onto a photodiode , it consist of an opaque cylindrical object (flag) between the light source and the detector to prevent the scattering of light the surface needs to be highly polished .

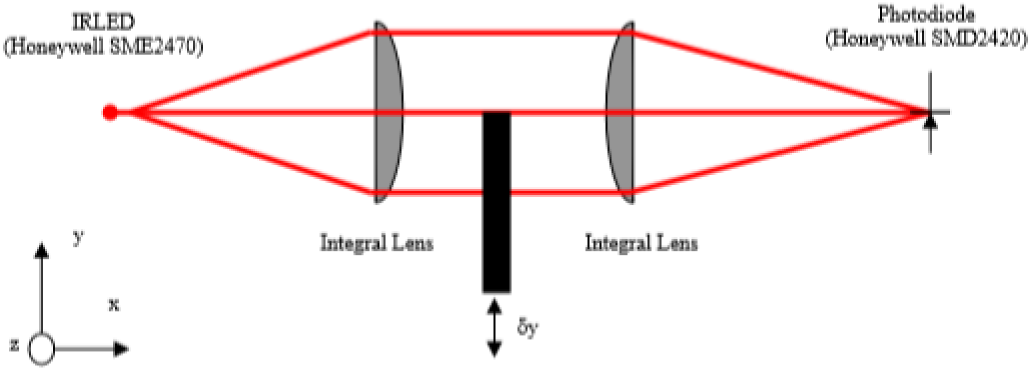

Fig4: Initial LIGO shadow sensor optical layout

The shadow sensor comprises of a flag , a surface mount single element photodiode, and a surface mount IRLED(infra-red light emitting diode) . The displacement of the flag in the Y-axis changes the proportion of light that is incident on the photodiode. There are two extreme conditions for the operation of the flag,

- When it completely covers all the light from the source i.e. zero light condition.
- When it is completely withdrawn from the path of light leading to full illumination on the photodiode i.e. maximum light condition.

A linear operating range can be determined between these two extremes. Under normal operating condition of the flag would reside at the centre of this operating range at half light position. The configuration shown above was employed in initial LIGO .

It was long suspected that the surface mount devices were the source of increased 1/f noise observed above shot noise at 1Hz and was later confirmed by Lockerbie [8]. Lockerbie also investigated alternative flag geometries, the final proposed scheme for advanced LIGO shadow sensor is shown in figure5. It consist of a mask with a slit , an integral lens, collimating , and a cylindrical flag , the collimating lens improves the collimation of the emission from IRLED, the mask ensures that only paraxial rays contribute to the noise floor . The IRLED and photodiode shown in figure7 was put forward as a replacement for original surface mount devices. The key parameters of the devices extracted from data sheet is shown in table2. Dimensions are the mask aperture is 1.5mm×4.5mm, and the mask-PD separation is 5mm.

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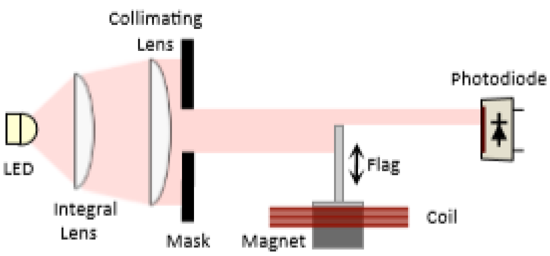

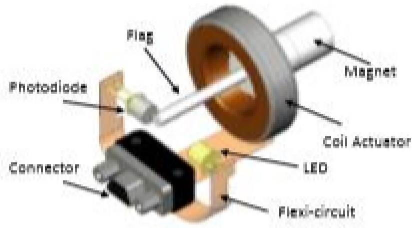

Fig5: cartoon showing the BOSEMs shadow sensing scheme.**Fig6**: Schematic of the integrated BOSEMs subsystems

Fig7: (Left) OPTEK OP232 IRLED. (Right) Centronic BPX65 photodiode

IRLED (OP232)	**PHOTODIODE**
TO-46 (Ø 4.7 mm) Kovar Package	TO-18 (Ø 4.8 mm) Steel Package
Anode to case	Cathode to case
Hermetically Sealed	Hermetically Sealed
Peak emission = 890 nm	Peak sensitivity =850nm
Maximum forward current = 100 mA	Responsivity = 0.55 A W-1 (at 900 nm)
Operating forward current = 35 ma	Capacitance = 15 pF
Maximum radiant power = 8 mW (at 100 mA)	Dark Current = 5 nA

Table 2: Key specification of leaded sensor components

1.1.1 SENSOR ASSEMBLY:

Electrical isolation requirements [13] state that the device must be isolated from aluminium carriers and hence from the rest of the structure .To ensure that this requirement is met, each device is insulated from the carrier by a ceramic sleeve into which the device is push-fit. A recess machined into this sleeve accommodates the flange and the flag located on the sensor package. A flat machined on the sleeve outer diameter, which corresponds to an aperture (pinhole) on the carrier enables the orientation of the device to be fixed during assembly process this ensures that the anode and cathode are correctly oriented. This technique is employed in both IRLED and photodiode assemblies. Figure8 shows the assembled IRLED carrier and a component part explosion. Figure9 shows equivalent photodiode assembly.

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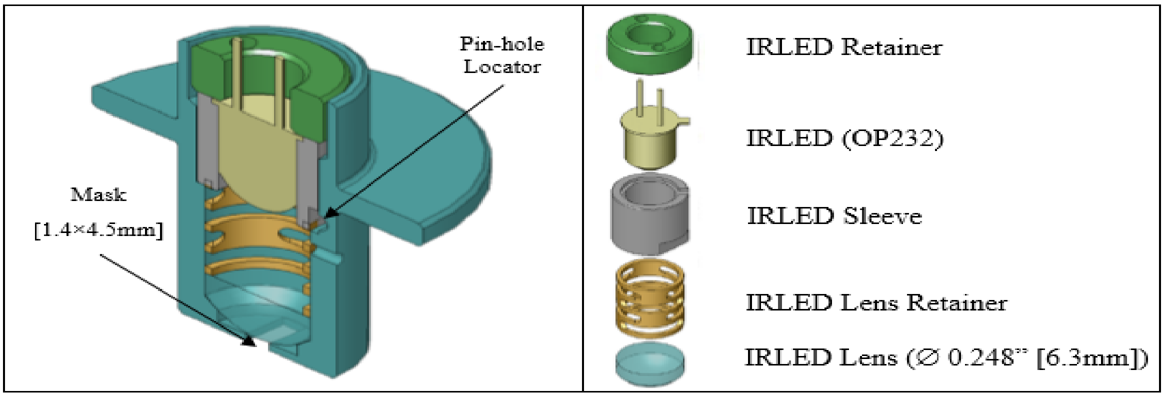

Fig8: (Left) Section through IRLED carrier. (Right) IRLED carrier part explosion.

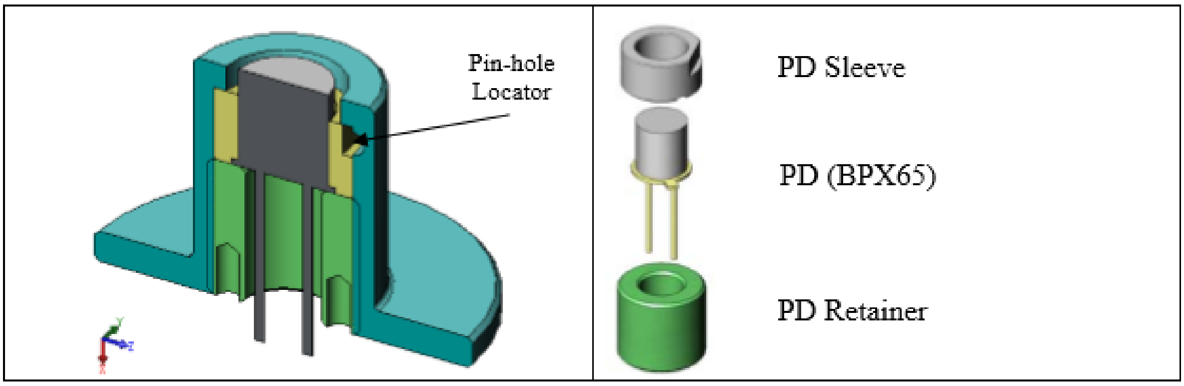

Fig9: (Left) Section through photodiode carrier. (Right) Photodiode carrier part explosion.

1.2 ELECTROMAGNETIC ACTUATOR:

Due to the change in suspended mass from initial LIGO there was a need to revive coil geometry to provide stronger actuation forces. The recommendations put forward by strain [5] has been listed below and is adopted,

- To add matched shielding magnets at the penultimate mass (PM) and upper intermediate mass (UIM) stages of the quad suspension.
- For the PM double the length or larger diameter magnets should provide sufficient force.
- In the case of the UIM, the 10mm long magnets should provide sufficient force. It is also necessary to double the length of coil.

Properties of electromagnetic actuator:

- Wire Type = 32QML, 32 gauge copper wire + quad layer coating of polyimide-ML.
- Coil former material = Aluminum (6082).
- Coil Inner Diameter = 0.7" [17.78mm].
- Coil Length = 0.315" [8.00mm].
- Number of Turns on Coil = 800.

Actuator characteristics:

- Maximum continuous coil current of 150 mA.
- Peak coil current 300mA (penultimate mass OSEMs only).
- Force constant of 0.22 N/ (A2 m2).

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- Coil winding clockwise when viewing the back face of the OSEM.
- Winding inductance = 3.1 ± 0.2 mH measured at 1 kHz.
- Winding resistance = 16 ± 1 ohm.
- Actuator coil is isolated from the OSEM body (> 100 M ohm).

The dimensions of coil former is shown in the figure10.

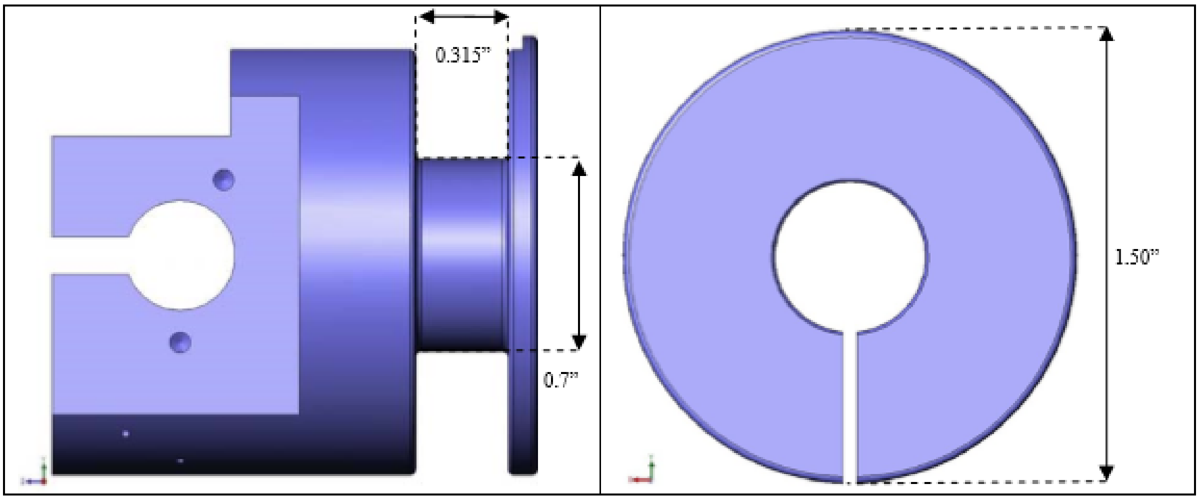

Fig10: Actuator coil-former geometry. (Left) Profile of coil-former. (Right) Front face of coil-former

1.3 MAGNET AND FLAG ASSEMBLY:

The operating point or sweet spot of the magnet and actuator has been calculated using a Mathematica model generated by Batron [14]. For these advanced LIGO suspensions Ø10mmX10mm long Nd.B-Fe nickel plated magnets have been selected. The flag magnet and former assemblies are shown in figure11.

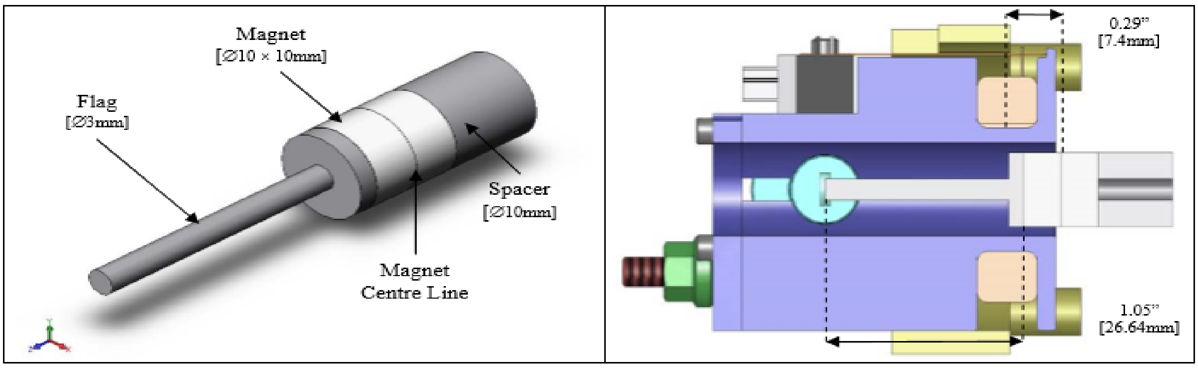

Fig11: Flag, magnet and coil-former assemblies. (Left) Isometric view of flag and magnet. (Right) Section through coil-former and flag.

To ensure that the residual actuation force is less than 5mN the use of magnetic materials in the construction of BOSEM is restricted. Suggestions regarding strength of magnet and dimensions is given byK.A. Strain [5].

1.4 INTERCONNECT DESGIN:

The interconnect design encompasses all the circuit routing and connections required to link together various electrical components of BOSEM, as well as provide an external interface for electrical connections . Figure12 shows the

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interconnect assembly including all individual parts to be connected. The anode and cathode are represented as A and K respectively.

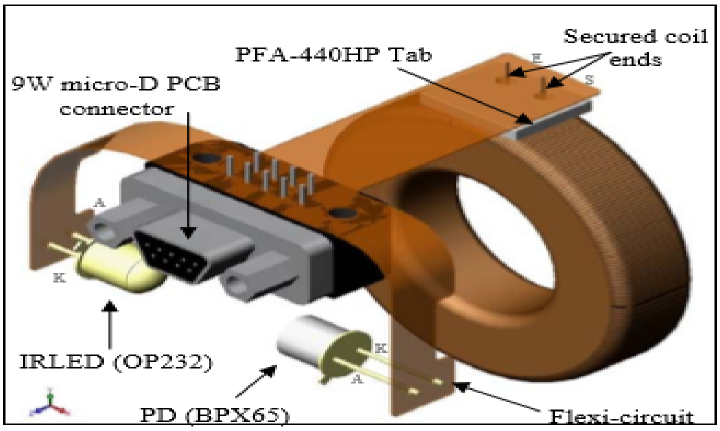

Fig12: Interconnection assembly.

Pin out of connector:

Pin	Signal name	Description
1	Pd-K	Photodiode cathode
6	Pd-A	Photodiode anode
2	IRLED-A	IR emitter anode
7	IRLED-K	IR emitter cathode
3	-	Not connected (on BOSEM head side)
8	-	Not connected (on BOSEM head side)
4	FN	End of coil winding
9	ST	Start of coil winding
5	Shield	Not connected on BOSEM head side

1.5 SATELLITE BOXES:

The ‘satellite boxes’ incorporate a current supply for the BOSEM LEDs, a voltage amplifier for the BOSEM PD signal, and provide electrical pass-through from actuation electronic units to the coils. Monitoring circuits are also included in the unit to monitor its activity and status. Each satellite box is equipped with four current sources and amplifier channels, serving four OSEMs units at a time.

1.6 COIL DRIVER:

The coil-driver units amplify the signal from the digital control system to drive the BOSEMs coils for actuating the suspended mass. Each coil-driver unit contains four current drive circuits, and also consist of a read back–circuitry which helps in remote monitoring of the unit’s performance. The coil-driver units serve two functions: First, to provide strong actuation authority for the damping of the motion of the suspended masses and to allow for acquisition of the interferometer system; Second, to provide quiet actuation to allow for control of the overall interferometer during detector science mode.

Principle of operation of the coil driver unit is shown in figure13, it consist of three stages the first stage is the input stage which is used to minimise coupling to electrical ground noise, the input to the unit from the DAC is differential and balanced with respect to ground. It also consist of two independent chains of amplifiers which prevent introduction of ground noise into the unit by keeping the electrical signals independent and symmetrical with respect to ground. The test mode and operational modes can be selected remotely by the user. The second stage consist of filters, Different

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numbers of low pass and/or high pass filters are implemented in the various units, depending on the specific type, and filters may be enabled/disabled within the unit according to the required operational mode. The final stage is the power output stage which consist of buffers and current amplifiers. Signals from the power output stage are sent to themonitor boards for diagnostics, before driving the BOSEM coils. In units with high current modes, based on the monitor board signals, a trip relay can disable the driver unit preventing overheating and damage of the coils which would occur if excessive currents are supplied to the coil for prolonged periods.

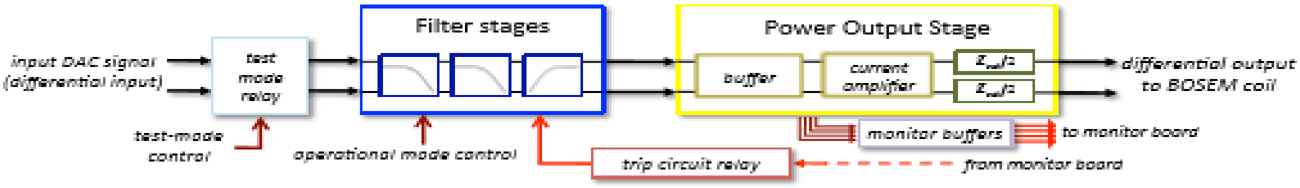

Fig13: Schematic of the coil drivers.

The coil driver mainly has three actuation functions

- 'Top' coil-drivers serve for the static alignment/positioning of the optics and correction of slow drifts, and more generally compensate for the very low frequency motion of the optics below 1Hz.
- 'Intermediate' coil-drivers control the low frequency suspension's dynamics in the frequency range between 1Hz and 10Hz.
- 'Lower' coil-drivers actuate at high frequencies (above 10Hz) and serve for interferometer lock acquisition ('acquisition mode') and lock maintenance ('run mode')

III. CONCLUSION

The presented paper provides a brief introduction to gravitational waves and the detection principles employed. It reviews the integrated systems of sensors and actuator systems involved in advanced LIGO. Detailed descriptions regarding the working of optical sensor, electromagnetic actuator, the magnet and flag assembly, satellite boxes and coil driver units is provided.

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