Ultra-stable Segmented Telescope Sensing and Control Architecture

Lee Feinberg[a], Matthew Bolcar[a], Scott Knight, Dave Redding
[a]NASA Goddard Space Flight Center, Greenbelt, MD; [b]Ball Aerospace, Boulder, CO; [c]Jet Propulsion Laboratory, Pasadena CA

ABSTRACT

Large segmented space telescopes that can achieve 10^10 contrast are under consideration for both the Large Ultraviolet Optical Infra-Red (LUVOIR) and Habex mission studies. The key challenge for this type of architecture is how to achieve sufficient stability to support this level of contrast. This paper will survey a few emerging sensing and control architectures and associated technologies that can potentially achieve the required stability. It will also provide a summary of the sensing and control portion of the LUVOIR segmented telescope architecture that has emerged from a recent design study and will provide a first look at the control methods that are being employed.

Keywords: ATLAST, LUVOIR, Exoplanet, HDST, Space Telescope

1. INTRODUCTION

NASA is currently funding four mission studies that are candidates for the 2020 Decadal Survery for Astrophysics. Two of these mission studies are considering segmented telescopes and one of the current studies, the Large Ultraviolet Optical InfraRed (LUVOIR) mission study, is studying an ultra-stable segmented architecture at two different sizes:

Architecture A – 15 meter telescope that folds up in an 8.4m SLS Block 2 shroud
Architecture B – 9.2 meter that uses an existing fairing size, and which will begin this Fall

This talk will summarize the ultra-stable architecture of the 15m segmented telescope including the basic requirements, the basic rationale for the architecture, the technologies employed, and the expected performance. This work builds on several dynamics and thermal studies performed for ATLAST segmented telescope configurations. The most important new element of the architecture was an approach to actively control segments for segment to segment motions which will be discussed later in this paper. While this work was focused on the 15 meter LUVOIR architecture, the basic approach is sufficiently generic to be applicable to both smaller (eg, 6.5 or 9.2 meter) or larger segmented telescopes for LUVOIR and possibly for Habex.

2. STABILITY REQUIREMENTS AND POTENTIAL REQUIREMENT RELAXATION STRATEGIES

A key driving requirement for future decadal study missions is to detect Exo-earths with 10^-10 system contrast which means contrast stability of 10^-11. This requirement equates to about 10 picometers RMS between updates but the driving requirement is for tip, tip and piston of segments as these are the most sensitive terms. Further sensitivity studies are planned but these degrees of freedom are believed to be the most sensitive based on their wavefront contribution and the fact that they fall in between the inner and outer working angle. The related requirement is how frequently the piston, tip, tilt would need to be updated. Work by Moore and Redding has studied this problem assuming a Zernike sensor correcting just these 3 degrees of freedom. Their conclusion for updates rates is:

- <5 seconds for a 6th magnitude star
- <2 minutes for a 10th magnitude star

Since the LUVOIR yield calculations assume 6-10th magnitude stars, we have set the requirement of 2 minutes for the update rate based on optical measurements of the science star. Thus, the entire system wavefront needs to be stable for up to 2 minutes. While this duration is heavily dominated by dynamics effects, thermal and creep effects do need to be considered.

While the 10 picometer RMS level is a reasonable goal at this point, there are several ways this requirement could be relaxed in the future. Some novel coronagraph approaches may be able to relax the telescope stability. The Vector Vortex type coronagraph relaxes certain symmetric aberrations but is sensitive to piston, tip, tilts and has not yet been shown to work well with a central obscuration like LUVOIR. The APLC coronographs can work well with obscured systems and work is going on to establish the sensitivity of these systems to piston, tip, tilt. An interesting idea that can be combined with either coronagraph is to add a non-telecentric microlens system that uses a pinhole behind the microlens that can essentially filter the rejected starlight from the planet through field diversity. Early modeling suggest this approach could relax both contrast and stability requirements by significant amounts and work is going on to demonstrate the physics of this approach both through modeling and testbed activities.

Another novel approach to relaxing stability requirements is to relax the timescale of updates. One approach to this is to use an artificial laser guide star which provides sufficient signal to noise to reduce updates to milliseconds (work led by Cahoy/MIT and Guyon and Males (UofA). This would allow closed loop control of the entire system including the primary mirror and can control at rates fast enough to even remove dynamics if the actuation system can keep up. A slightly simpler version that would provide closed loop control would to insert a point source at the object plane of the coronagraph that can be seen with a Zernike sensor and which can allow closed loop control of everything behind that object point (this doesn't include the primary mirror but does include deformable mirrors).

Another approach to relaxing requirements is to use PSF calibration techniques as being employed on WFIRST and HST. The challenge of this is to know what type of noise sources one can expect at that level. It may be possible to combine PSF calibration methods with the laser guide star method to post process the data (so don't try to do closed loop control).

As can be seen, there are several promising ideas to relaxing stability requirements and all of them are actively being worked on. However, the 15m LUVOIR architecture did not assume any of these methods. It assumes we need to achieve a total of 10pm RMS stability, dominated by piston, tip, tilt, and for up to 2 minutes before the optical outer loop controls out drifts. The archicture here is consistent with that plan and any relaxations resulting from these novel approaches will only make the problem easier in the future.

3. LUVOIR 15 METER ARCHITECTURE

The LUVOIR 15 meter architecture was designed to be the largest telescope that can fit inside of an 8.4 meter SLS next generation fairing. The mirrors are hexagonal and slightly smaller than JWST segments. The mirrors are closed back ULE which provides a stiff, low CTE architecture.

To efficiently pack the entire observatory into the fairing, we have used a circular folding architecture with 2 wings on each side of the center section. This approach builds upon the approach used for the ATLAST 9.2 meter with a Delta IV Heavy 5-meter shroud. The idea is that a wing is attached to a wing using the same basic deployment motors, latches, hinges and motions as used on JWST wings.

Figure 1 shows a top level optical layout of this system which is a Three Mirror Anistigmat with a fine steering mirror. Figure 2 shows the telescope folding. This architecture is based on the architecture developed for the ATLAST 9.2 meter telescope with further improvements in the stability architecture[i].

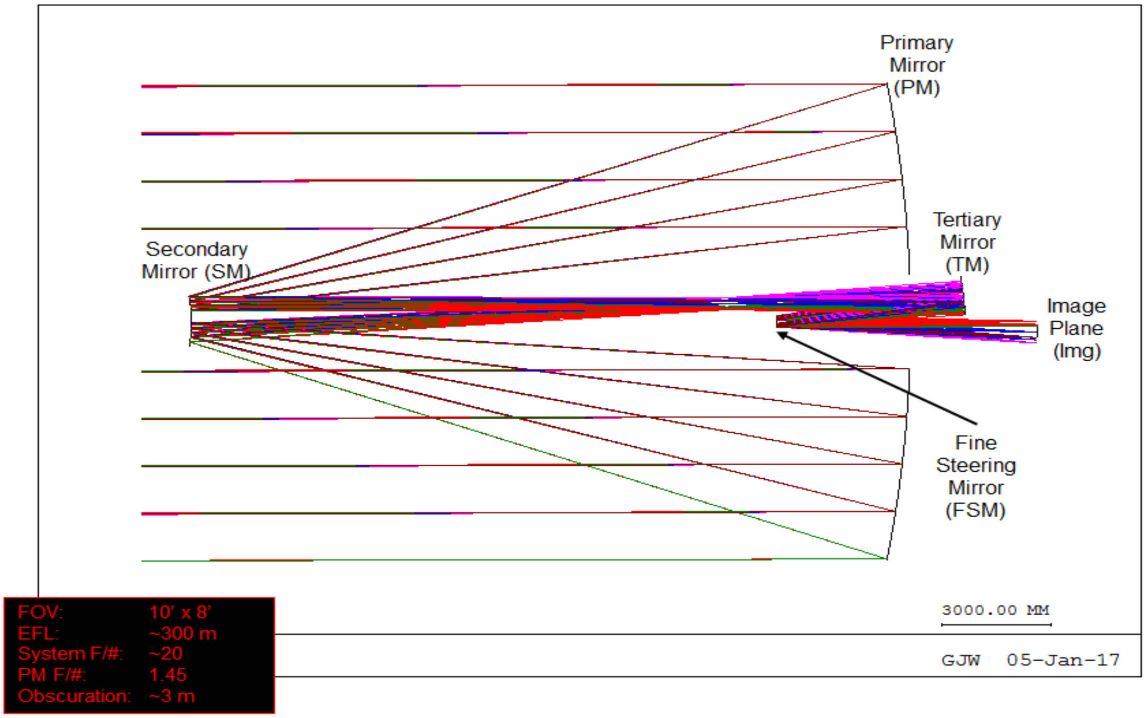

Figure 1: LUVOIR Optical Layout

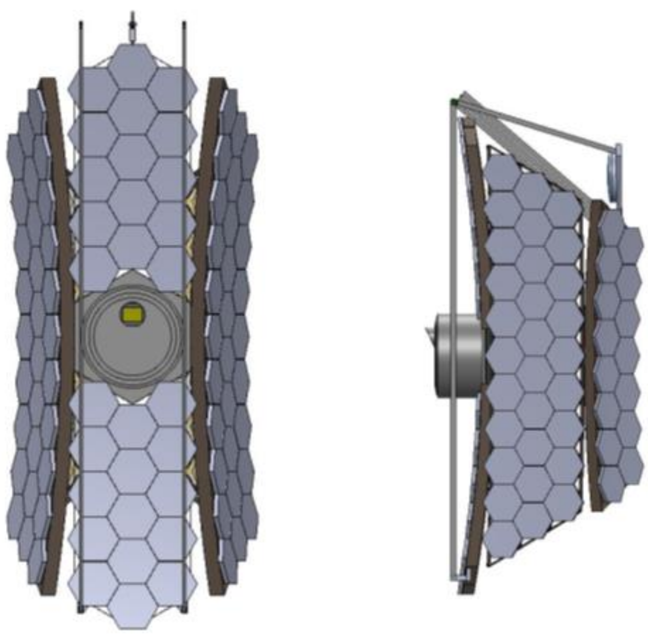

Figure 2: LUVOIR 15m Folding Architecture

4. LUVOIR 15 METER ARCHITECTURE

The LUVOIR stability architecture is based on some simple concepts for stable mirror segments, isolation, and control:

- Assume stiff mirrors (>300Hz) and picometer thermal stability achieved with 1mK heater plate (as demonstrated for ATLAST 9.2m)[ii]
- Use a Non-Contact Isolation approach (eg, Disturbance Free Payload) to sufficiently isolate the telescope for dynamics (>1hz). Modeling for 15m ongoing, based on success of pm stability for 9.2m ATLAST which also achieved excellent SM stability
- Use a Zernike Sensor in the coronagraph for the outer control loop for the primary mirror piston, tip, tilt updates (2 minute update for piston, tip, tilt)
- Use edge sensors and piezos to control primary mirror segment drifts (1hz to 2 minutes)
    - 450hz readout, 2 sensors per side on 3 sides similar to the Thirty Meter Telescope architecture
    - Capacitive edge sensors chosen due to heritage from ground telescopes
        - Laser truss also feasible which provides a common reference
        - Achieve good <1pm stability between edge sensors and piezos over 2 minute intervals

A key idea is to put the sensing and control at close proximity at the side and behind the mirrors respectively. In the past, the control was to be performed inside of the coronagraph at a deformable mirror but that runs the risk of added instability between the sensor and control which could make the control loop more complicated.

These simple principles lead to an architecture which requires relatively control of drift in the primary mirror segment positions. Since the edge sensors are on the edge of each mirror and the piezo actuators will be integrated onto the 6 hexapod actuators on each mirror, we have developed an overall electronics architecture with a single electronics box titled the Mirror Support Control Electronics (MSCE) that control the 6 coarse stage actuators, 6 piezo fine motion actuators, and the edge sensor readouts. A special edge sensor data router is used and the telescope control occurs in the Main Electronics Box (MEB).

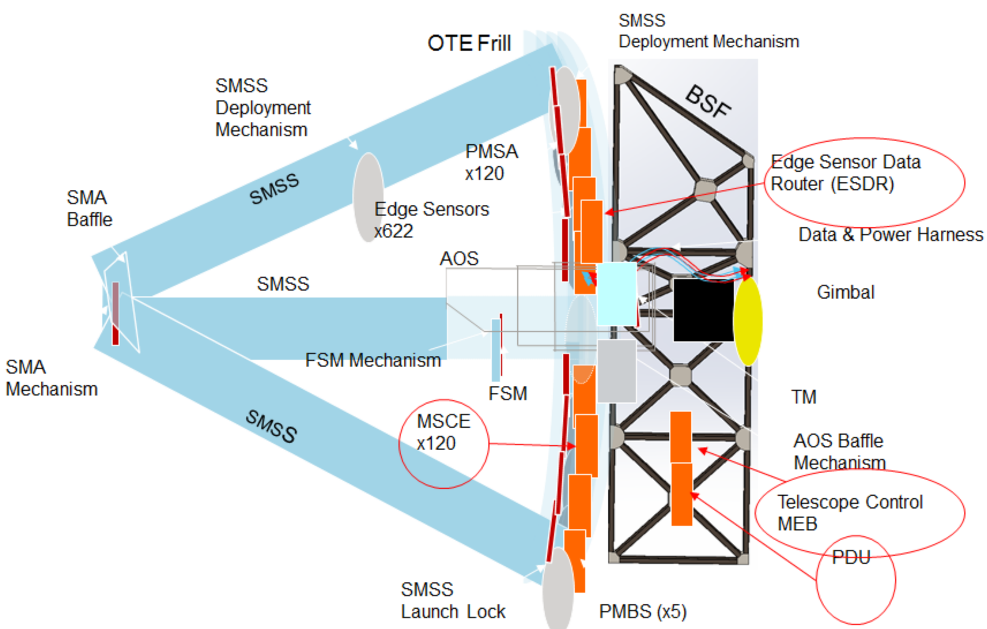

Figure 3: Basic Architecture of Stability Architecture Electronics

A basic block diagram of the overall architecture can be seen below in Figure 4. A Control System Process (CSP) is used to provide overall control of the primary mirror system by taking edge sensor readings and converting the to actuator control. The next level of details in the control block diagram is shown in Figure 5. In that figure one can see that the CSP interfaces to the MSCE and also provides heater control.

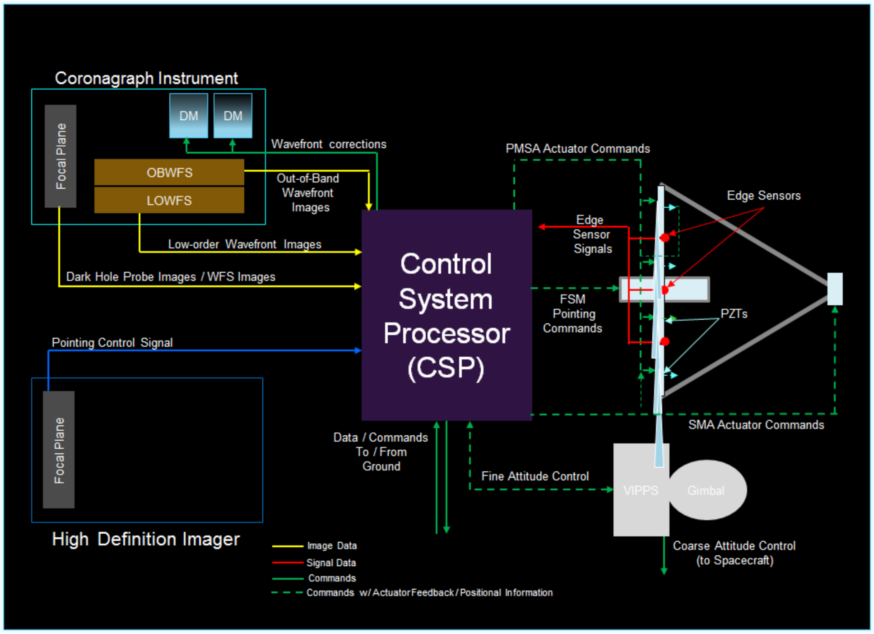

Figure 4: Control Architecture

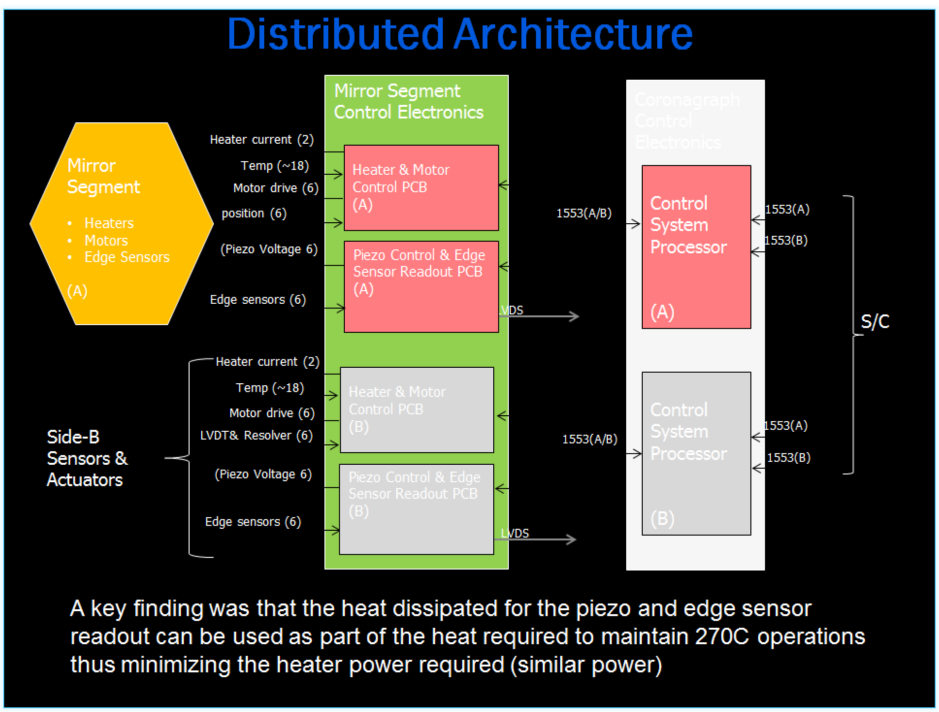

Figure 5: Distributed Control Architecture

The other aspect of the overall top level architecture is the Primary Mirror Segment Assembly thermal architecture. Shown in Figure 6, the mirror is controlled with a heater plate that itself is controlled to 1mK. The mirror is an adiabatic cavity that keeps it well controlled. The backplane will also be temperature controlled. The heat from the MSCE will be use as a cold bias starting point for the backplane temperature and the backplane will use heaters to carefully control the interface of the mirrors. Detailed modeling of the backplane and separately of the mirror gives the team confidence that 1 mK control can be achieved.

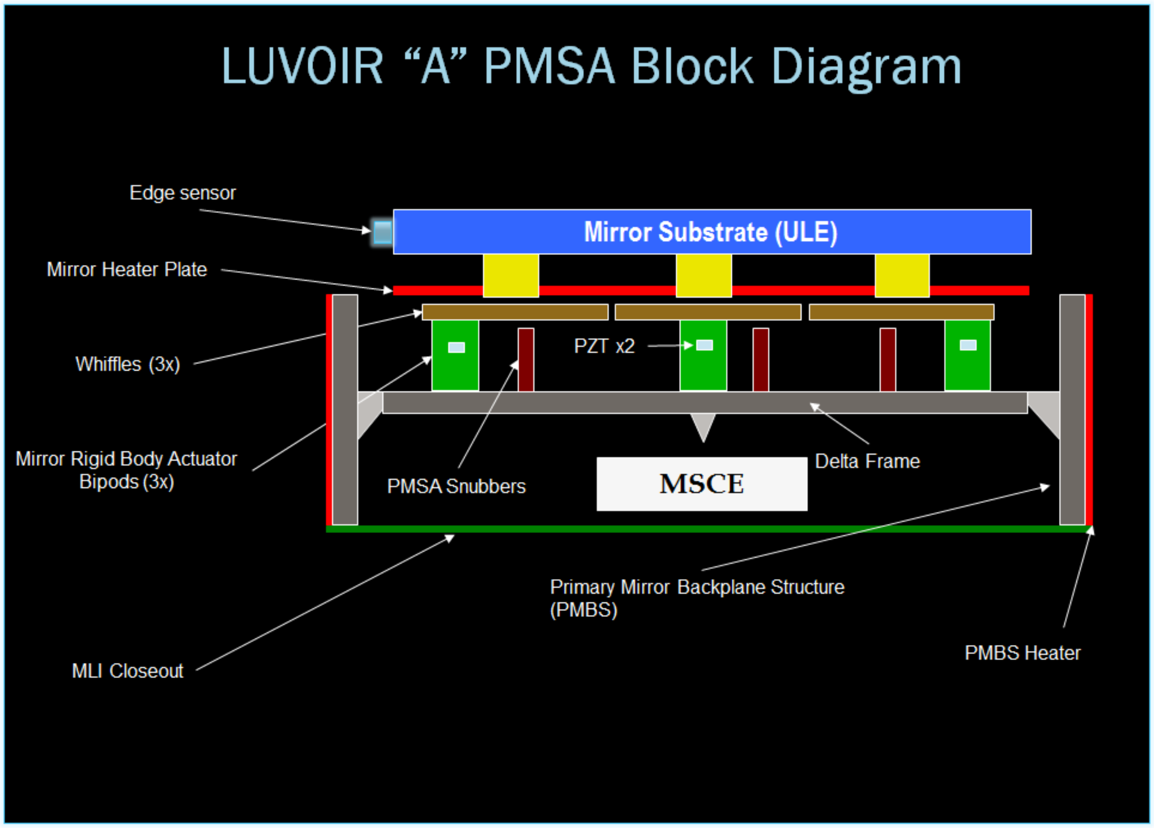

Figure 6: Mirror Thermal Architecture

5. ARCHITECTURE HERITAGE

The overall sensing and control architecture selected leverages actuators and edge sensors that have been demonstrated in the laboratory at levels similar to what is needed. The key innovation is to combine piezo control that has been demonstrated to picometer level in the lab with actuators similar to those used on JWST mirrors. This allows both a coarse mode which can deploy and align mirrors with a fine level of control used in the control loop. To do this, the piezos can be placed in way that they are not in the load path of the actuator but before the final linkage therby allowing a mechanical advantage between the piezo actuator and the motion. An error budget demonstrated that the piezos will need approximately a 3nm dynamic range and with a goal of 1 picometer level resolution of motion. A demonstration article of the piezo and a custom capacitive edge sensing for 3 degrees of freedom is shown in Figure 7 and was developed by Ball Aerospace for a Fabry Perot Etalon. Ball has demonstrated better than 10 picometer control and edge sensing. A key aspect of this approach is to maintain stability between the edge sensors on the side of the mirror and the piezo fine stage. Modeling has shown the largest contributor to this can achieve this stability with 1mK control.

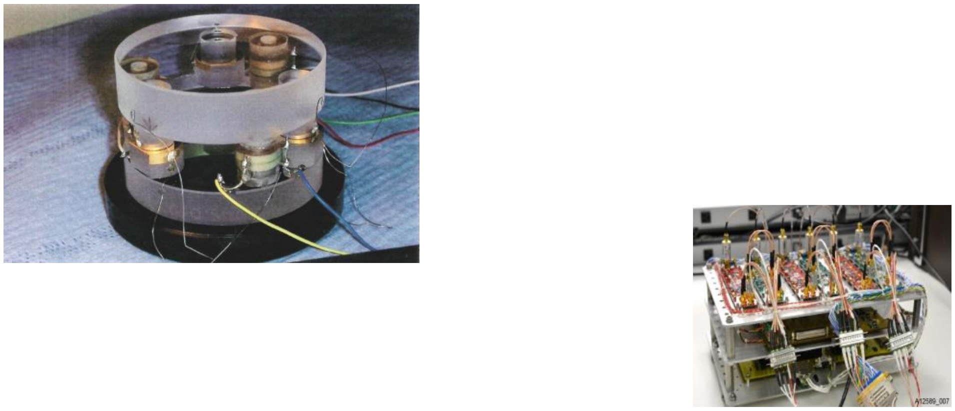

Figure 7: Ball Aerospace Sensor and Control Demonstration Article

In addition to the work that Ball Aersopace has done on capacitive edge sensing, ground telescopes have also demonstrated multi segment control using capacitive edge sensors. The Thirty Meter Telescope (REFERENCE) testbed has demonstrated nanometer level sensing and control and this provides an excellent starting point for the overall global motion. If just tip, tilt and piston are required, local control can be achieved by locking to a single reference mirror. Averaging can be used to beat down sensor noise. The baseline is to limit dynamic vibration using good isolation (REFERENCE)

The actuator being leveraged from JWST can be seen in Figure 8 below. The actuator includes 3 bipods that allow 6 degree of freedom adjustment of each segment. Other actuators that incorporate piezo control are feasible too but this provides a good starting baseline for power, mass and volume.

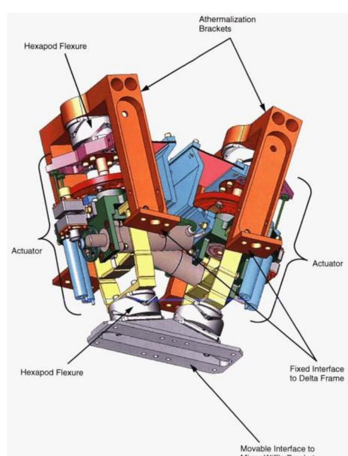

Figure 8: Heritage JWST Actuator

Another critical question is the thermal controllability of the path between the edge sensors and the control. This is primarily ULE mirror in between with epoxy and Titanium mounts and interfaces that can generally be configured out of the direction of sensitivity. As shown in Figure 9 and 10, the 1 mK level of control has now been demonstrated with a test article and the next step will be to demonstrate with a real mirror and heaters.

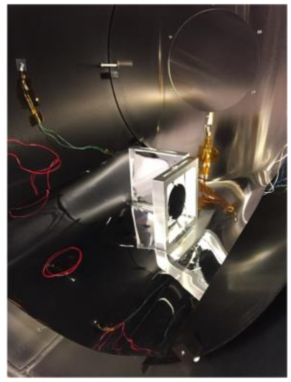

Figure 9: Surrogate Test Article that Demonstrated 1 Milli-Kelvin Control

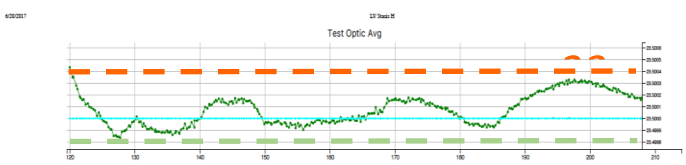

Figure 10: Surrogate Test Article that Demonstrated 1 Milli-Kelvin Control

6. CONCLUSION

The ultra-stable architecture for the 15m LUVOIR telescope has been developed that greatly leverages work by ATLAST studies and from heritage hardware. The key aspect of the architecture is to use edge sensors and piezo control which relaxes backplane requirements and inoculates the design to drift from creep and related changes. The full system dynamic performance is currently being analyzed for the 15 meter architecture but is based on the ATLAST 9.2 meter work that was modelled. The mirror stability is based on work done for the ATLAST 9.2m architecture. The sensing and control approach combines heritage from ground telescope sensing and control and leverages JWST actuator work and technology developments in the area of capacitive edge sensing and control.

7. REFERENCES

[i] Feinberg, L. D., Jones, A., Mosier, G., et al. 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9143, 16

[ii] Eisenhower, ATLAST ULE mirror segment performance analytical predictions based on thermally induced distortions, SPIE Proceedings