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The Purpose, Plan, and Progress of the Giant Magellan Telescope Primary Mirror Off-Axis Segment Test Cell

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ABSTRACT

Large aperture telescopes require active control to maintain focus, collimation, and correct figure errors in the Primary Mirror (M1) due to gravity and thermal deformations. The Giant Magellan Telescope (GMT) M1 active optics subsystem consists of the hardware and software that controls the shape, position, and thermal state of each mirror segment. Pneumatic force actuators support the weight and control the surface figure while linear position actuators control the six solid-body degrees of freedom of each mirror segment. A forced convection system comprised of fan-heat exchanger units control the mean temperature and thermal gradient of each mirror segment. The M1 Subsystem design leverages existing technology and employs innovations driven by more demanding requirements compared to heritage systems. These differences led to the identification of three key GMT project risks: determining if the vibration environment induced by the fan-heat exchanger units and the error in the applied influence functions required to shape the mirror are within image quality budget allocations. The third risk is incorporating damping to the force actuators to meet the seismic requirements. GMT is currently mitigating these risks by integrating a fully functional off-axis M1 Test Cell at the University of Arizona's Richard F. Caris Mirror Lab. This paper summarizes our requirements and design presented at the M1 Subsystem Preliminary Design Review in June 2019, describes our risk burn-down strategy for the M1 Subsystem, and presents our integration and test progress of the M1 Test Cell.

Keywords: Test Cell, Primary Mirror, Active Optics, Force Actuators, Hardpoints, Thermal Control, Control System, Damping

1. INTRODUCTION

The Giant Magellan Telescope (GMT) is a next generation extremely large ground-based telescope that will explore the formations of galaxies, the mysteries of dark matter, and characteristics of planets orbiting neighboring stars.[1] The GMT optical system provides a 25-meter diameter diffraction limited aperture to achieve the clarity and sensitivity needed for observing these astronomical phenomena.[1] The photons journeying through the vastness of space are collected by the Primary Mirror (M1) which is comprised of seven 8.4-meter diameter mirror segments. Each mirror segment is supported by an active optics control system, the M1 Subsystem, to maintain collimation and correct figure errors due to gravity and thermal deformations. The M1 Subsystem

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controls the first bounce of light in reaching the GMT's mission of revolutionizing our understanding of the universe.[1,12]

The M1 Subsystem has five primary functions (see cell layout in Figure 1): 1) float the primary mirror segments against gravity by applying distributed forces to the back surface of the mirror without inducing excessive stress to the glass, 2) provide 6 degrees-of-freedom (DoF) positioning to each mirror segment enabling active alignment of the GMT optical system, 3) provide support actuator force control to allow active correction of the low-order mirror figure errors, 4) protect the primary mirror segments during seismic events, 5) control the mirror temperature to maintain thermal equilibrium with the enclosure ambient temperature and reduce thermal gradients across each mirror segment surface.[2]

The requirements to achieve these functions were derived from successful active optics systems on the twin Magellan Telescopes, the Large Binocular Telescope, and unique characteristics of the GMT. This paper will provide an overview of the key and driving requirements and the resulting design innovations to satisfy these requirements. GMT Organization (GMTO) has decided to manufacture a full scale and fully populate a M1 Subsystem called the Test Cell. It will be used to validate these requirements and mitigate the risk of implementing these innovative solutions. This paper will provide an overview of the risks that drive the purpose of the Test Cell and a snapshot of the Test Cell integration progress.

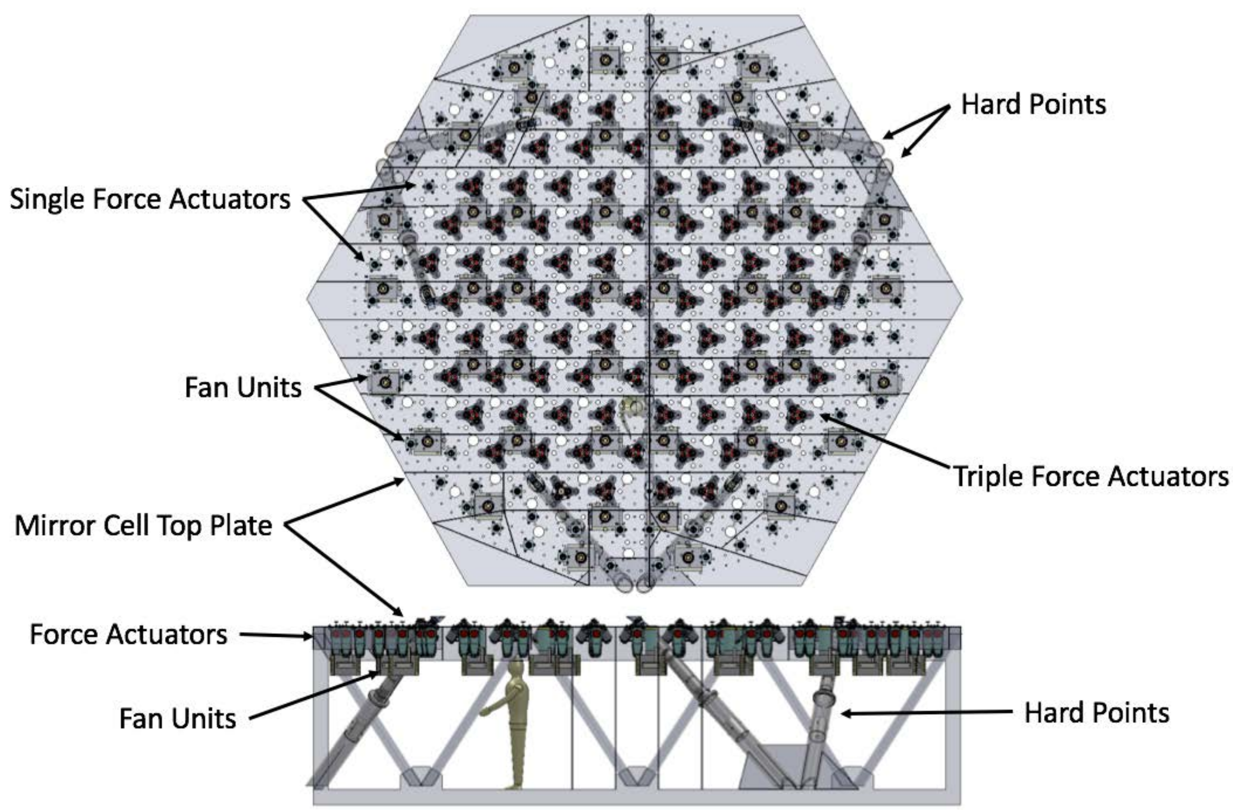


Figure 1: **M1 Subsystem Layout within an Off-Axis Mirror Cell**

2. M1 SUBSYSTEM DESIGN OVERVIEW

The GMT M1 Subsystem is an active optics control system that provides the static support, active support, and thermal control of the primary mirror segments.[2] Figure 1 is a depiction of the M1 Subsystem layout for an off-axis mirror cell. Figure 2 shows solid model renderings of the primary components of the M1 Subsystem.

The static supports are wire rope isolators mounted to the top plate of the cell. They support the mirror when the mirror is at rest and provide part of the damping during a seismic event. Dampers, located inside the support actuators, provide the remaining required damping.

During observations, the mirror segments are floated by force actuators also referred to as support actuators which carry the weight of the mirror segment. These are single-axis and triple-axis support actuators arranged to enable cell interchangeability and provide active control of the mirror surface figure. The position actuators, called the hardpoints, control the six rigid-body degrees of freedom of each mirror segment and provide an active control of the mirror position with the accuracy necessary to phase the mirror segments and achieve a single 25 meter primary optic of the telescope.

The thermal control system uses a closed loop forced convection system. Air handlers that consist of a fan and heat exchanger, pressurize the cell and force air through nozzles into the honeycomb structure of the backside of the mirror to provide control of the mirror temperature.[5] The software control of the integrated M1 Subsystem is implemented in the M1 device control system using the GMT software frameworks and an agile software development process.[9] The M1 Subsystem design was reviewed at the M1 Subsystem Preliminary Design Review (PDR) held in June 2019.

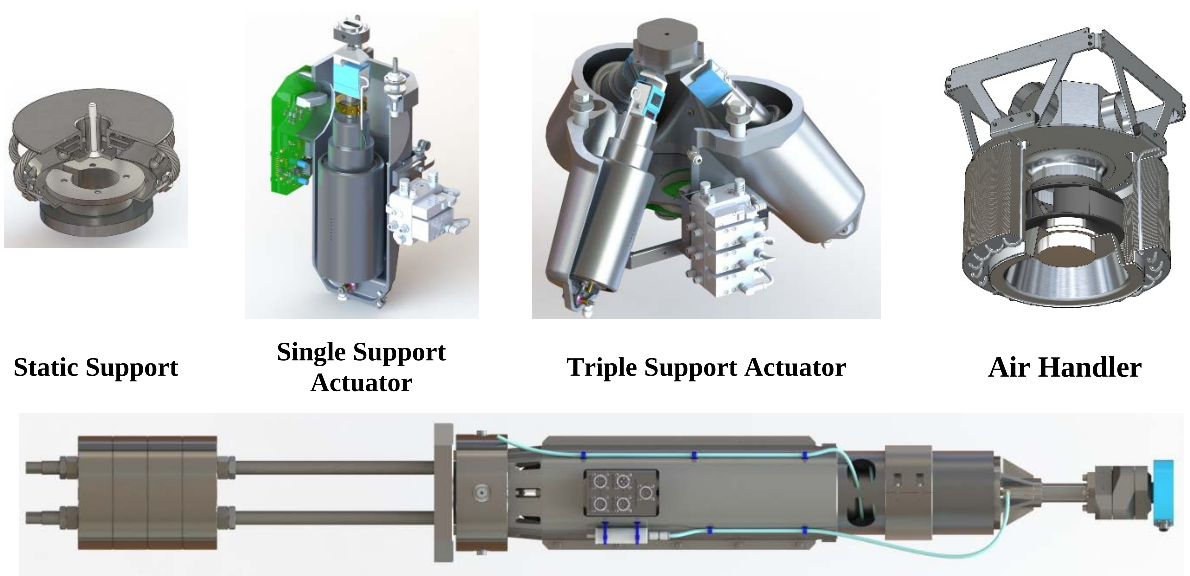


Figure 2: M1 Subsystem components

3. KEY AND DRIVING REQUIREMENTS

The M1 Subsystem design is informed by several key and driving requirements that are derived from a combination of legacy telescope systems and unique characteristics of the GMT. The 25-meter diffraction limited aperture drives tighter vibration requirements and interchangeability of the support actuators. Each mirror segment active optics control system leverages proven methods on the Magellan Telescopes and the Large Binocular Telescope for defining glass safety and thermal performance requirements. These and other requirements are described below.

3.1 Interchangeable Cells

The six off-axis mirror segment cells are required to be interchangeable on the telescope structure to reduce fabrication and operational costs. This is achieved by reducing the number of different part types manufactured and maintained in inventory. As a result, each off-axis cell should be capable of operating in any of the six off-axis locations. The support system needs to respond to the gravity vector which changes with the zenith angle as well as clocking of the 6 off-axis locations. Therefore, GMT has implemented 3-axis support actuators that apply force to the mirror in the x, y and z directions where the legacy telescopes used 2-axis support actuators.

3.2 Glass Safety

The active optics support system is designed to ensure that the glass is not subject to excessive stress throughout the life of the telescope. The University of Arizona Richard F. Caris Mirror Lab has done extensive simulations and testing of specimen glass pieces to define the principal glass stress limits that ensure glass safety. Thermal and annealing stress are not set as requirements but are allocated 0.7 MPa each. The requirements for mechanical stress are specified as a limit of 0.7 MPa stress lasting more than 5 minutes and 1.0 MPa transient stress lasting less than 5 minutes per event. The mechanical stress is further divided into global and local stress. The application of force to the glass results in a bending of the glass, this creates stress throughout the glass known as global stress. Local stress is defined as peaking of stress in the glass where point loads are applied. The stress is budgeted as 0.35 MPa for global stress and 0.35 MPa for local stress to constrain the mechanical stress in the glass. The stress limit informs various design choices for all the subcomponents and components in the M1 Subsystem; for example, the force that can be applied by the hardpoint breakaway or the maximum force that the support actuators can apply.

3.3 Seismic Requirement

The GMT is being built in a seismically active region of Chile. The safety of the telescope, especially the 8.4-meter diameter mirror segments, is of the utmost importance. The Observatory level requirement for a seismic event has been specified as 1% probability of M1 glass failure over 50 years.[4] Detailed analysis of the site-specific seismic environment and its effect on the GMT has been performed and the impact on the M1 Subsystem resulted in increasing the range of travel of the support actuator air cylinders from +/- 30 mm to +/- 40 mm to prevent the air cylinder from bottoming out during a seismic event. Similarly, the static support range of motion requirement was revised to 24.5 mm in the axial direction and 26.2 mm in the radial direction. The analysis has also shown that adding a 1000 Ns/m to 2000 Ns/m damping to the support actuator air cylinders significantly reduces the risk of damaging the glass during a seismic event (Figure 3). The M1 Subsystem team is currently developing dampers to be integrated within the support actuator air cylinders that apply forces in the same degree of freedom as the air cylinders.

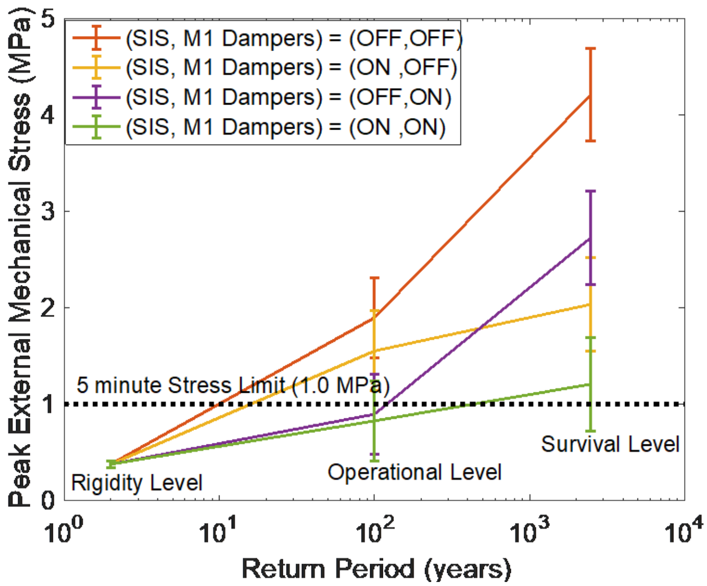


Figure 3: Effect of the GMT Seismic Isolation System (SIS) and M1 support actuator damping on mirror stress[4]

3.4 Thermal Performance

The GMT thermal system tracks the mean temperature of the glass relative to the ambient air. Analysis using temperature records at the site show that a time constant of the thermal system of < 40 minutes can track the ambient temperature to within less than 0.2K following error for 50% of the time (Figure 4). This satisfies the Observatory level requirement to maintain image quality.[5] The analysis also recommends a heating or cooling capacity of more than 2 K/hour. These requirements are further verified by Computation Fluid Dynamics analysis of the mirror segments.[6] The M1 Subsystem team is currently developing a force convection closed system to meet these requirements.

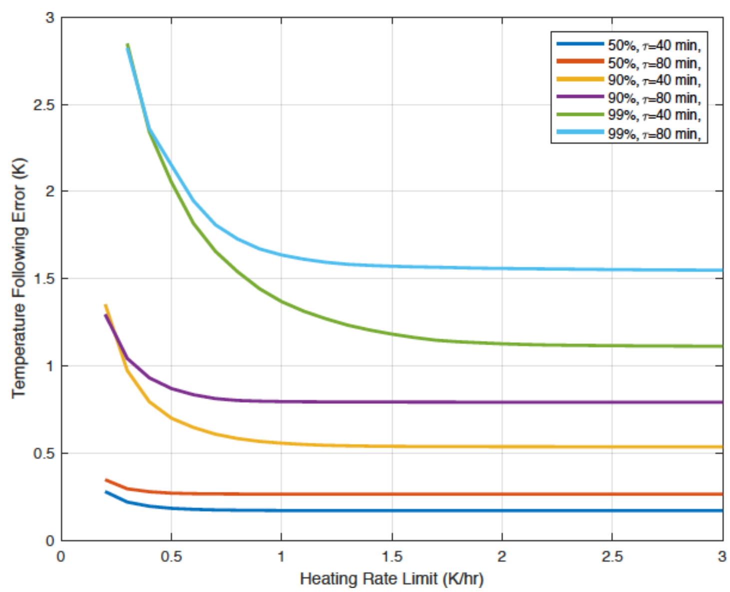


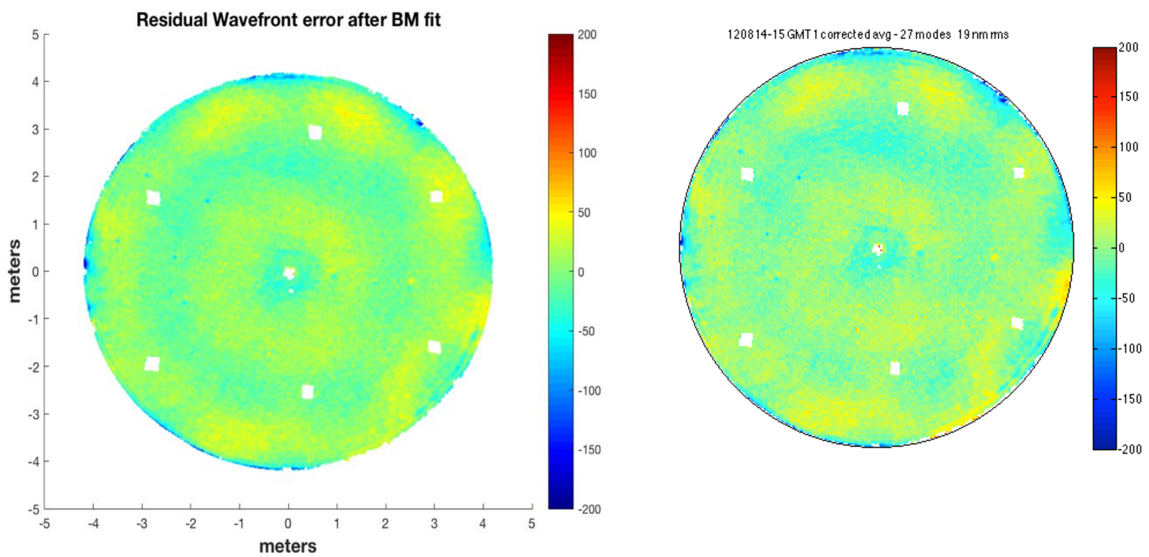
Figure 4: Median and 90th percentile temperature following error as a function of thermal time constant and heating/cooling rate limit[5]

3.5 Vibration Budget

GMTO is concerned about the impact of vibration in the telescope on the image quality. The M1 Subsystem potential vibration sources include the high frequency chattering of 350 pneumatic valves in the support actuators and the harmonic vibration of the fans used in the thermal control system. The limit has been set to ~0.7 milli-arcseconds RMS of resulting tip tilt image motion, after fast speed tip tilt correction, for the whole M1 Subsystem.[7] The budget is being evaluated through detailed analysis and tests planned with the Test Cell. Vibration isolation designs to mitigate the effects of vibration induced by the M1 Subsystem on image quality is one of the key requirements that will be tested using the Test Cell.

3.6 Active Optics Requirement

The GMT active optics loop simulation shows that each segment needs to correct the 27 lowest order static bending modes of the mirror to meet the image quality requirement.[8] To ensure that the 27 bending modes can be controlled, it is important to measure the influence matrix of a mirror segment. The influence matrix[ii] derived from Finite Element Models at GMTO were verified against the influence matrix derived by the Mirror Lab for GMTO mirrors. The polishing error map of GMT S-1 was corrected by using the 27 lowest order bending modes to verify the influence matrix calculations. The residual surface figure error calculated by GMTO and by the Mirror Lab are shown in Figure 5 which are nearly identical. Similar comparisons were performed for the gravity support force distribution matrices.



(a) (b)

Figure 5: **Mirror polishing error after active optics correction. Surface map is in nm. The first 27 bending modes of the mirror are corrected. (a) Simulation results from GMTO. (b) Simulation results from the University of Arizona Richard F. Caris Mirror Lab.**

[ii] The influence matrix is the transformation from applied forces to normal displacement at the surface of the mirror.

3.7 Position Sensitivity and Accuracy

The GMT active optics loop requires the hardpoints to maintain position and optical alignment between the primary and secondary mirrors which requires greater sensitivity than legacy telescope systems. The Hardpoint is required to measure its overall length with a resolution no greater than 100 nm, to have a force resolution non-repeating force error tolerance no greater than 1 N, and to have an axial stiffness greater than 120 N/micron. These requirements flow down from the observatory natural seeing image quality budget.

3.8 EtherCAT Compatible Hardware

GMTO has adopted EtherCAT as an observatory wide fieldbus protocol. All the control hardware in the M1 Subsystem is required to be EtherCAT compatible. The M1 Subsystem implements a custom device controller and electronics design using EtherCAT that is described in section 4.8.

3.9 Vacuum Compatibility

The complete M1 cell with the glass segment will be placed inside a vacuum chamber for coating the mirrors. The interior of the cell is required to maintain a dirty vacuum of 0.1 Pa; therefore, all the M1 hardware that cannot be easily removed and reinstalled during the mirror coating process must survive this vacuum environment. This requirement imposes constraints on material selection of the electro-mechanical hardware used in the cell.

4. INNOVATIVE SOLUTIONS

The key and driving requirements have led to unique challenges for the design of M1 Subsystem which are being addressed by implementing innovative design solutions. For example, dampers are being developed to apply damping along the active direction of each air cylinder. This clever application significantly reduces the lifetime mirror stress exposure as seen in section 3.3, Figure 3. This section describes some of the innovation solutions applied to satisfy the M1 Subsystem requirements.

4.1 Support Actuators Castings and Manifolds

The maintenance of seven mirror cells will be far more challenging than the legacy single segment telescopes. There are 1,174 support actuators that contain 2,406 air cylinders, 112 air handlers, and 42 hardpoints. There is a plethora of moving parts that will require regular maintenance. To reduce this maintenance challenge, the support actuators are being designed as line replaceable units which led to two main design choices.

First, the support actuator housing is made of a single sand aluminum casting rather than from multiple fastened sheet metal plates. This reduces the number of parts, eliminates fastened joints, streamlines the fabrication process, and controls internal interfaces. 183 of 350 air cylinders have been assembled for the Test Cell and the M1 Subsystem team is currently integrating the first batch of support actuators. Figure 6 shows the single-axis and triple-axis support actuators.

Single Support Actuator **Triple Support Actuator**

Figure 6: Single and triple support actuator assemblies with a manifold and a control board

Second, the pneumatic supply to the single and triple actuators were modularized. The pneumatic supply to every actuator has its own pneumatic circuit to ensure safety under individual actuator failure. The pneumatic circuits consist of the main control valves, check valves, and orifices to bleed the air cylinder. This circuit is implemented in a compact manifold for every support actuator. This reduces the air supply utility interface for each actuator to a single pneumatic tube. Each manifold type has a custom cable harness that prevents misconnection of the valves and provides a single connector interface to the support actuator electronics. These design solutions enable the valve manifold to be tested as a single unit and easily replaced for servicing. Figure 7 shows the manifold for single and triple actuator assemblies. All valve manifolds for the Test Cell have been received.

Single Valve Manifold **Triple Valve Manifold**

Figure 7: Single and triple support actuator valve manifolds with harness

4.2 Actuator Calibration System Design with the Motion Stage

The support actuators for the M1 mirror segments are calibrated before they are installed into the cell. This ensures that systematic errors in the actuator assembly are characterized and reduced. The calibration is performed with the actuator calibration system which consists of a special calibration stand, electronics cabinet, and control software. The calibration stand allows the support actuator to apply a force at a rigid node (live node) on the calibration stand. Precision loadcells on the calibration stand measure the force and moment applied by the actuator at the live node. A least square fit between the commanded force and the measured force provides the calibration matrix.

The support actuators are designed to apply normal force vectors to the back surface of a mirror segment: triples-axis support actuators apply both normal and in-plane forces and the single-axis support actuators apply only a normal force. Misalignment in the actuator assembly and the rod end bearings of the air cylinder can induce a moment error in the final force applied. A novel motion stage has been developed that mimics the motion of the mirror to simulate the range of motion and velocities that the support actuator rod-end bearings will experience in operation. The motion stage uses the same hardpoint mechanism and control software in the hexapods that simulates the mirror motion on the live node. Figure 8 is an image of the actuator calibration system with the static stand. The rods with flexures will be replaced with the hexapod actuators. Since the motion stage uses the hardpoint controller, the actuator calibration system will also be used for early testing of the hardpoint electronics and software to be used in the M1 cell. The M1 Subsystem team has demonstrated calibration of a support actuator using the actuator calibration system.

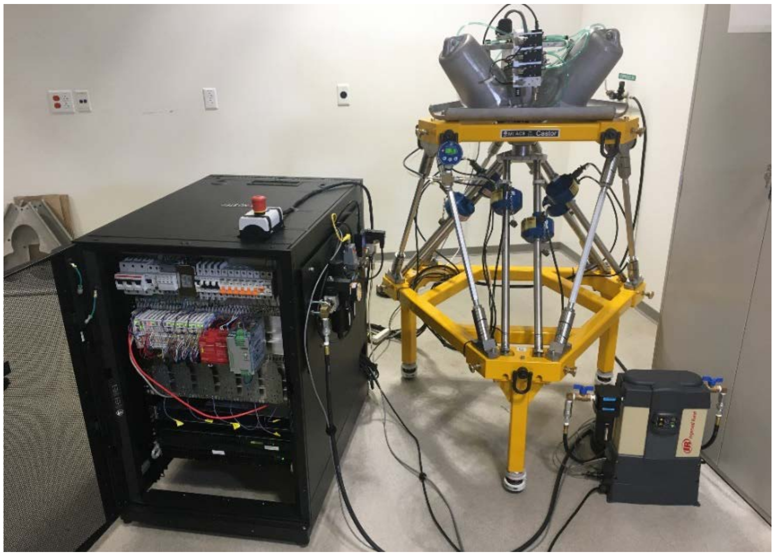


Figure 8: M1 Actuator Calibration Stand with Motion Stage

4.3 Air Cylinder Dampers

To meet the seismic requirements described in section 3.3, various designs to add dampers to the air cylinder have been explored. Only passive dampers can be considered because power may not be available to the cell during a seismic event. There are two types of dampers in development, an eddy current damper and a hydraulic damper. The selected damper is being designed to fit inside the air cylinder with the applied force vector oriented in the same direction of the air cylinder. The eddy current damper seen in Figure 9 is the preferred method because of the vacuum requirement described in Section 3.9. Hydraulic based dampers are less suitable because of their propensity to leak fluid near the mirror surfaces. The damper design is challenging due to tight constraints of available volume, the need to minimize coulomb friction, and a desire to maximize damping. The eddy current damper simulation and prototype testing has shown providing enough damping to reduce mirror stress during a seismic event is feasible; however, reducing the friction is challenging. The team is currently developing bearing techniques to minimize or eliminate the friction and sourcing eddy current damper suppliers. An alternate hydraulic damper that can meet the vacuum and friction requirements is also being developed to mitigate cost, schedule, and technical risk of the eddy current damper development.

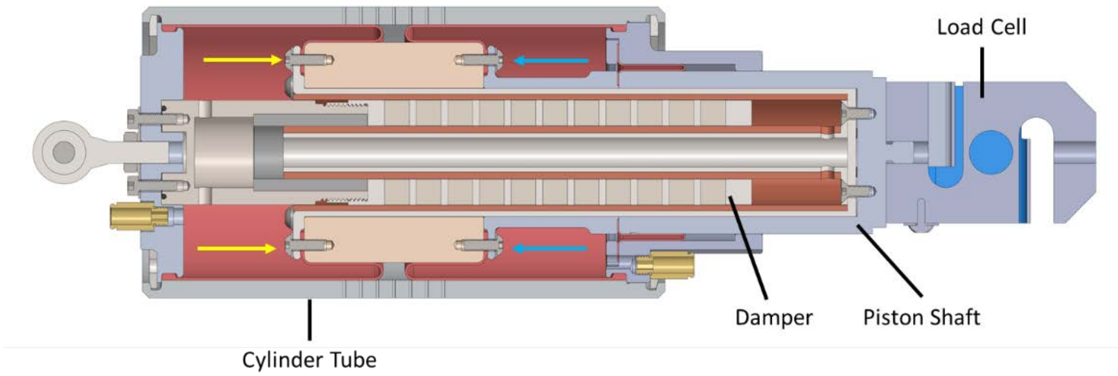


Figure 9: Support Actuators Air Cylinder Cross Section with Eddy Current Style Damper

4.4 Hardpoints

The six DoF rigid body motion of each M1 mirror segment in their respective mirror cells are defined by six custom linear actuators arranged in a hexapod pattern. The linear actuators, known as Hardpoints, are used to maintain position and optical alignment between the primary and secondary mirrors. The hardpoints are capable of sensing axial loads applied by the mirrors due to gravity, wind, and inertial loads from telescope slewing and seismic activity. The hardpoints utilize a precision lead screw coupled to a motor providing a 160:1 gear reduction. This enables the hardpoint to provide the increased sensitivity and accuracy requirements relative to legacy systems. Three hardpoints have been manufactured and are currently being assembled for functional testing. Figure 10 shows one of the completed hardpoint assemblies.

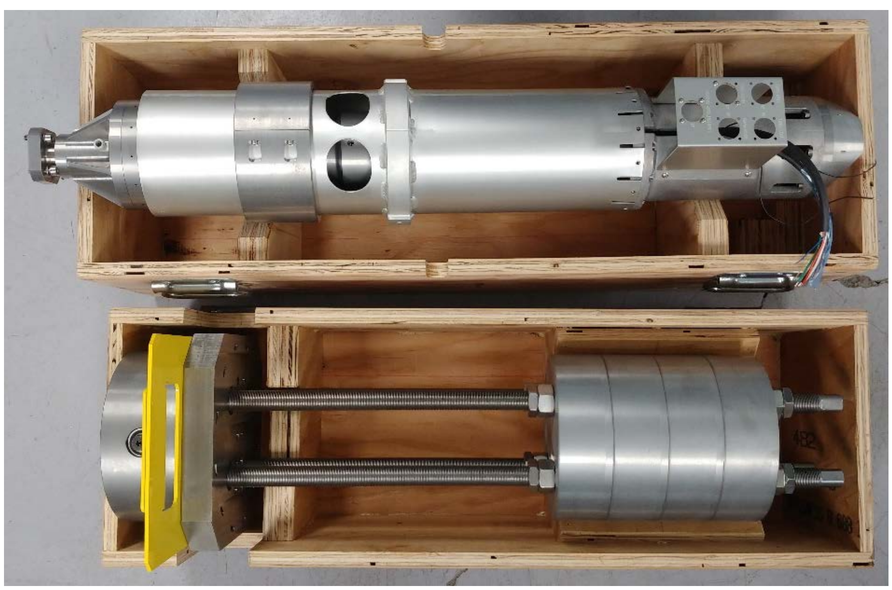


Figure 10: Hardpoint Actuator and Counter-balance Weight Assemblies

4.5 Thermal Control System Design

The mean temperature and temperature gradients in the mirror are controlled by flushing the hexagonal cores of the mirror with ambient temperature air. This is achieved by pressurizing the lower plenum using fans as shown in Figure 11. The blue arrows indicate the air flow path. The air is drawn from the upper plenum by the fans, passed over and cooled by the heat exchangers, and pushed through the nozzles into the mirror cores. This forms a closed loop convection system similar to legacy systems. This design was optimized by reducing the number of fans, adding ducting to direct the intake air flow, and using CO_2 as the heat exchanger coolant. These design enhancements increase the thermal performance efficiency by reducing the sensitivity to heat sources in the lower plenum with better mixing of the air in the cell. CFD simulations have been performed to understand the thermal performance effect on image quality. The main contributions to the image quality currently being studied are dome seeing effects and the mirror figure error due to thermal gradients in the mirror.[9] The M1 Subsystem team recently completed the thermal control system trade study and is currently preparing for a thermal control system delta Preliminary Design Review.

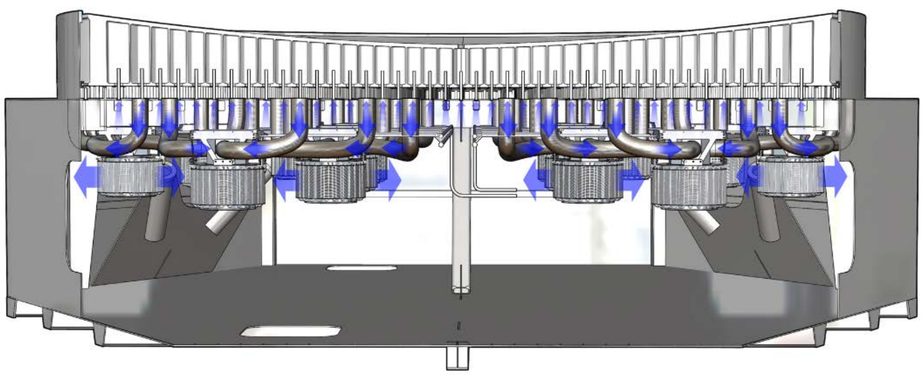


Figure 11: Thermal System Design

4.6 EtherCAT and Power Hub Distribution Boards

The M1 Subsystem contains over 225 EtherCAT slaves which could lead to significantly complex cable routing. The initial construction and ongoing maintenance of the cells requires reduced complexity of wiring in the cell. By customizing the Power over Ethernet technology for the custom EtherCAT devices, a two-thirds reduction in cabling can be achieved. This is accomplished by developing EtherCAT and Power Hub (EPH) distribution boards. Additionally, the EPH provides centralized power management and diagnosis of each support actuator communications link. The EtherCAT slave allows the central control system to monitor and control the component slaves attached to the EPH. Power control circuits provide and monitor power to each component slave. The EPH serves as an additional control point for power to each support actuator which enhances mirror safety by providing redundant control of the support actuators.[10] All the EPH boards needed for the Test Cell have been fabricated, board level tested, and one has been tested with a set of 16 support actuators boards as seen in Figure 12.

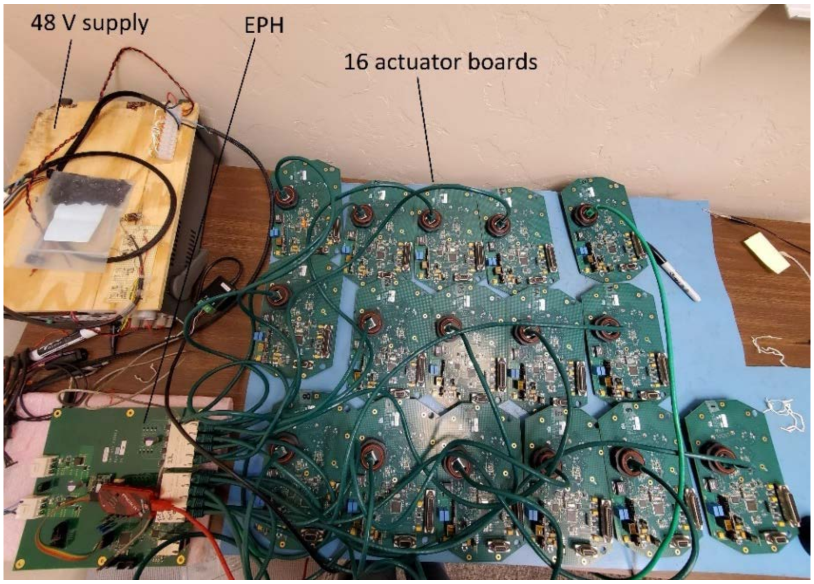


Figure 12: EtherCAT and Power Hub Board (EPH) with 16 Support Actuator Boards

4.7 M1 Control Law and Software Implementation

The control software consists of control laws and sequences for the active optics control, thermal control, and system safety. GMTO has characterized the generic control laws and sequences for supporting and shaping the mirrors by leveraging the primary mirror control software of the Large Binocular Telescope.[11] These control laws are being implemented in the real-time control software for the primary mirror. The M1 device control software is implemented using the GMT core software frameworks and is developed using agile software development process.[9]

5. RISK MITIGATION

The M1 Subsystem team follows the GMT risk management process that involves continually assessing new risks and actively burning down existing risks. A risk register is maintained for identification, rating, and tracking the M1 Subsystem risks. The three highest risks are shown in Table 1. Each of these risks have a burn down strategy that is incorporated into the Test Cell schedule. The validation of the support force influence matrix analysis and the characterization of the thermal system vibration environment risks are what drive the need to fabricate the Test Cell and test the system with a mirror segment. The new damper development risk is driven by a low technical readiness level because it is a novel application for an active optics control system.

The first listed risk is the support force influence matrix analysis. The M1 Subsystem is designed to correct the shape of the mirrors at all operational pointing angles of the telescope. The M1 Subsystem has analyzed the bending modes required to correct their shape and has incorporated that into the control algorithm design for the support actuators. The University of Arizona, which produces our 8.4-meter diameter mirror segments, supports the mirror during polishing and mirror figure testing in an arrangement that is slightly different then that the M1 Subsystem. The difference in applied loads to the back surface of the mirror may affect the ability of the M1 Subsystem to meet the image quality error budget; therefore, this risk receives a “High” ranking. The risk will be reassessed when the testing with a mirror segment has been accomplished.

The next listed risk is the thermal control system vibration environment. The thermal control system makes use of air handlers to recirculate air from the cell into the honeycomb core of the mirrors. The air handlers are attached to the cell weldment thereby causing vibration of the telescope structure. The previous baseline design also included a circulating pump for the glycol coolant; however, this has been replaced with CO_2. The vibration budget allocation for the pump is being redistributed to the air handlers. These sources of vibration could degrade the image quality of the telescope; therefore, this risk receives a "High" ranking. The M1 Subsystem team has made great strides in advancing the design of the thermal control system and two of the mitigation strategies outlined in Table 1 have been incorporated. The risk will be reassessed when the prototype air handler has been tested with the vibration isolation system.

The last high risk is the damper development. The M1 Subsystem is required to protect the primary mirror segments from excess stress during seismic events over the 50-year life of the telescope. As stated earlier, damping is being incorporated into the support actuator air cylinder design to reduce mirror stress. The GMT is the first telescope to use dampers in this application which gives the dampers a low technical readiness level rating; therefore, this risk receives a "High" ranking. The eddy current damper is currently on its second design cycle and poses a cost and schedule risk to the Test Cell. Damper surrogates have been incorporated into the air cylinders to facilitate the damper development in parallel with the active optics control system development. The Test Cell schedule includes allocated time to replace the damper surrogates with dampers prior to performance testing of the Test Cell with the mirror simulator.

Risk Title	Risk Statement	Rank	Response
Support force influence matrix analysis	If the difference in the figure of the mirror from the change in applied force location between the mirror polishing cell and Test Cell are greater than the image quality error budget, then the error budget for natural seeing and the adaptive optics budget would be impacted.	High	1) Develop influence matrix model and compare to legacy models 2) Fabricate and test the M1 Subsystem with and off-axis mirror to validate the control algorithm can shape the mirror within the adaptive optics budget using the test tower at the UA
Thermal system vibration environment	If the measured vibration of the air handling system exceeds the vibration budget, then image quality of the mirrors may be impacted.	High	1) Incorporate isolation to air handler design 2) Remove pump by switching to CO_2 coolant 3) Perform testing of prototype air handler 4) Measure vibration environment produced by the thermal control in the Test Cell
New damper development	If the eddy current damper design is not completed and validated in time to support Test Cell performance testing, then the Test Cell schedule may be delayed.	High	1) Develop an alternate fluid damper design in parallel with eddy current development 2) Conduct a design review prior to prototype fabrication and testing of both designs 3) Fabricate and test damper prototypes integrated with an air cylinder 4) Down select damper design

Table 1: M1 Subsystem High Risks

6. TEST CELL PURPOSE

The primary objective of the Test Cell is to mitigate the risks described in Section 5 by determining that the mirror support forces can be controlled within the image quality budget and the fan vibration environment is within its system level allocation. The Test Cell will be used to validate the control system by performing functional, performance, and safety testing with a mirror simulator prior to committing to integration of a mirror into the Test Cell and production of the M1 Subsystem components. The Test Cell will serve as an interface check to freeze the M1 Subsystem-to-Mount interfaces. Lessons learned throughout the component and system level integration and test of the Test Cell will be tracked and evaluated for incorporation into the design update for the production M1 Subsystem. Lastly, the procedures developed during the Test Cell will be used to optimize the M1 Subsystem production plan.

7. TEST CELL PLAN

GMTO has established an integrated product team with partner organizations, the University of Arizona (UA) and Texas A&M University (TAMU). The GMT M1 Subsystem team oversees the M1 Subsystem development and Test Cell integration and test activities with responsibility for the program performance, system test planning and execution, procurement, and component level testing. The UA is providing subject matter expertise, engineering and technician support, and the specialized facilities for the custom electronics and Test Cell integration and test. TAMU is providing engineering support and the facilities for the integration of the air cylinders and support actuators. Other component level integration and testing including the hardpoints will be performed at the GMT facility in Pasadena, California. Peer reviews, component level qualification and performance testing, and our quality management system are used for early identification and resolutions of problems. Lessons learned are being documented and workshops will be conducted to incorporate design modifications for production. Figure 14 shows a high-level integration and test flow diagram and the steps highlighted in grey are completed.

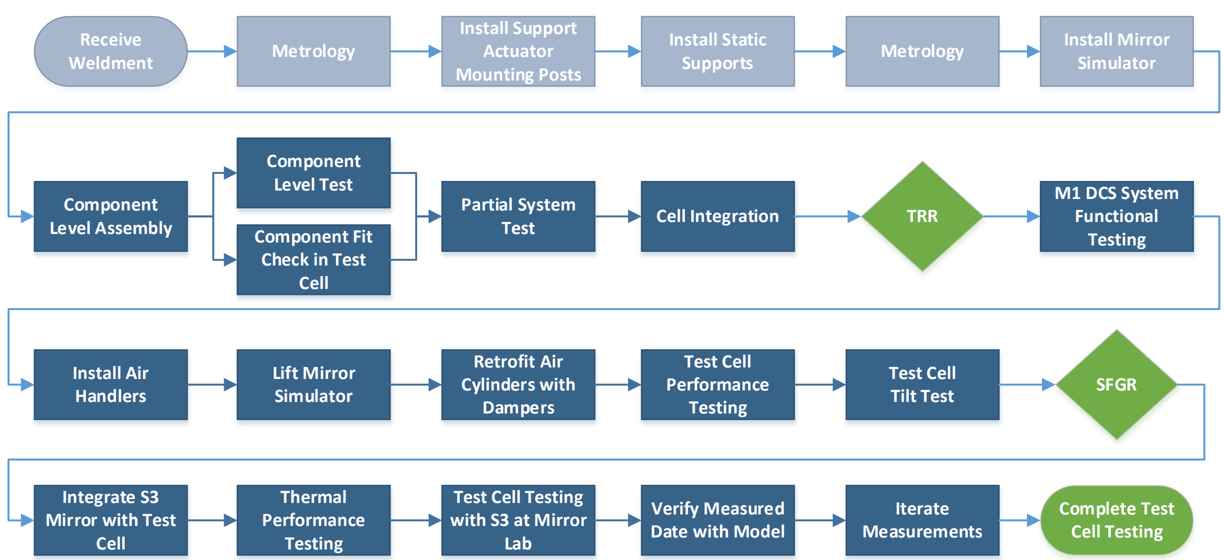


Figure 14: Test Cell Integration and Test Flow Diagram (grey signifies completed)

The Test Cell integration and testing began with the receipt of the Test Cell weldment at the UA and alignment of the top plate features. Once the support actuator mounting posts and static supports alignments were completed, the mirror simulator was secured to the static supports. The support actuator, support actuator electronics board with the EPH board, and hardpoint component level integration and testing are currently occurring at TAMU, UA and GMTO, respectively. The team is preparing for the fit check of the support actuators and one hardpoint in Test Cell for early identification and resolution of issues. Multiple partial system tests are planned to resolve software and hardware interface issues before system level testing. For example, an EPH system bench test is planned that combines the EPH boards with the support actuator electronics boards and cell control cabinet to test lower level software functionalities. A Test Readiness Review (TRR) will be conducted before starting integrated system level testing to assure the system and procedures are ready for system level testing.

With the authorization to proceed from the TRR, the M1 Subsystem team will then begin functional testing with a key milestone of lifting the mirror simulator with the active support system. The thermal control system will be integrated in parallel with functional testing and refactoring of the M1 device control software to incorporate the action items from the functional testing. There is a break in the schedule to install the dampers which is the schedule risk mitigation of the damper development explained in section 6. After the Test Cell is completely integrated with the dampers and thermal control system, performance and safety testing will commence. All functional, performance, and safety tests will be repeated with by putting the test cell on a tilt jig. The Test Cell will be positioned on a stand that tilts the entire Test Cell at 13.5° to simulate the inclination of the cell on the telescope when the telescope is pointing zenith. The test cell will also we clocked at 0° and 120° to simulate the clocking of the off-axis segments. These tests will verify that the M1S hardware and software works for different zenith angles and clocking angles. This section of the Test Cell Integration and test flow will conclude with a Safe for Glass Review (SFGR) to assure the active optics control system is safe for integrating with a glass mirror.

With the authorization to proceed from the SFGR, a GMT off-axis mirror segment will be integrated onto the Test Cell to advance with the main objective of the Test Cell. The purpose of the M1 Test Cell is to measure the influence matrix of one of the GMT segments under the test tower at the Richard F Caris Mirror Lab at the UA using the Test Cell integrated with an off-axis mirror segment. This measurement is the last test to be performed and will consist of three test campaigns using the test tower at the UA. The test tower contains an interferometer that provides the highest fidelity system available for conducting these precise measurements. The surface figure measurements to derive the influence matrix will be done through a nulling interferometer technique or through a Software Configurable Optical Test System (SCOTS) setup specifically designed for GMT off-axis mirrors. The nulling interferometer and the SCOTS test results together provide high fidelity results for both low spatial frequency and high spatial frequency errors, thus increasing the SNR of the measured influence matrix. [13] The UA uses this facility for polishing the mirror segments. For legacy telescopes, the final mirror cell with the mirror segment were tested in the test tower and the measured influence matrix was directly used for active optics correction on the telescope. GMT will have the opportunity to test only one mirror segment with its final control hardware. The remaining six segments will use the influence matrix calculated by the finite element models (FEM). Hence, the measurements acquired using the test tower and the Test Cell are extremely important for validating the influence matrix derived from the FEM and building confidence that it can implemented for all segments on the telescope.

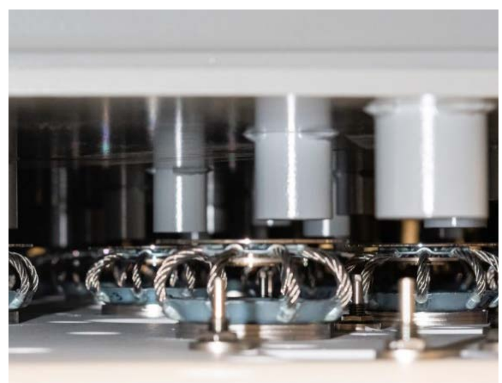
8. TEST CELL PROGRESS

The M1 Test Cell weldment and mirror simulator both fabricated by CAID Industries in Tucson, Arizona, were delivered to the Richard F. Caris Mirror Lab at the University of Arizona. The top plate force actuator mounting posts and static supports alignment has been completed and the M1 Test Cell has been integrated with the mirror simulator (Figure 15).

The force actuators are being assembled at TAMU who have received all the components to assemble the air cylinders, completed assembly of 183 of 350 air cylinders, and is currently integrating the first batch of support actuators. The fabrication of three hardpoints has been completed and the team is currently integrating the hardpoints and preparing for functional testing as well as a fit check with the Test Cell. The thermal control system requirements definition and design trade studies are completed, and the thermal control system delta PDR is planned for first quarter 2021.

The M1 Subsystem device control system has completed 10 sprints and demonstrated force actuator control, support actuator calibration using the actuator calibration system, and hardpoint control by closing the velocity and position loops using the prototype hardpoint. Lastly, the control algorithms for the support actuators have been developed and demonstrated on a prototype single and triple support actuator.

Test Cell Integrated with Mirror Simulator



Static Supports and Support Actuator Mounting Posts

Figure 15: Test Cell Integration Pictures

9. SUMMARY

The Giant Magellan Telescope (GMT) Primary Mirror (M1) active optics subsystem consists of the hardware and software that controls the shape, position, and thermal state of each mirror segment. The M1 Subsystem design leverages existing technology and employs innovations driven by more demanding requirements compared to heritage systems. These differences led to the identification of several GMT project risks that are currently being mitigated by integrating and performance testing an off-axis mirror segment cell at the University of Arizona's Richard F. Caris Mirror Lab. The Test Cell has completed integration of the mirror simulator with the Test Cell weldment, assembled over 180 of 350 air cylinders, integrated two actuator calibration systems, and assembled of three hardpoints. The software team has demonstrated functionality of the hardpoint controller, support actuator controller, and support actuator calibration in the static stand. The M1 Subsystem team is currently developing the air cylinder damping and thermal control system. The next phase of integration is component level testing and integration into the Test Cell.

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