Repurposing the James Webb Space Telescope's center of curvature optical bench hexapod for future mirror calibration testing at NASA Marshall's x-ray & cryogenic facility

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ABSTRACT

The James Webb Space Telescope's (JWST) center of curvature optical bench (CoCOB) hexapod was repurposed to enhance NASA Marshall Space Flight Center's X-Ray & Cryogenic Facility (XRCF) optical metrology capabilities. This upgrade unlocked higher test article load capacity and extended the allowable ranges of motion of the CoCOB hexapod. The hexapod was also coupled to a new long-stroke, linear motion axis to form a 7 degrees of freedom system and allow for high precision testing of larger diameter test articles. A 9 degrees of freedom motion system, consisting of a three-axis linear mount in an X-Y-Z configuration and a commercially available hexapod, was also designed to allow high resolution positioning of the focal plane instrumentation over a large range of motion. A modern control architecture and graphical user interface was developed for the CoCOB hexapod and additional motion stages to permit streamlined commanding and operation. This paper discusses the justification for re-using the CoCOB hexapod by highlighting its unique precision motion control capabilities in a high vacuum and optically clean environment. The design, key component selection, and environmental compatibility for each of the additional motion stages is presented along with testing results for achieved range, repeatability, and minimum step size performance for all motion axes. Finally, a summary of the motion control system architecture and its flexibility to address tomorrow's optical metrology needs are presented.

Keywords: hexapod, precision positioning, multi-DOF positioning, motion stage, optical metrology, mirror calibration, X-Ray & Cryogenic Facility

1. INTRODUCTION

As part of NASA Marshall's X-Ray & Cryogenic Facility (XRCF) upgrades [1], a suite of precision motion systems were designed, built and delivered to enhance NASA's optical metrology capabilities. The motion suite consists of two complementary components: one component for positioning the test article and the other for positioning the metrology equipment (Figure 1). The test article positioner is the repurposed center of curvature optical bench (CoCOB) hexapod, which is now referred to as the mirror adapter module (MAM) hexapod, additionally augmented by a 1 degree of freedom (DOF) transporter stage. The second component, used to position metrology equipment, is a three orthogonal axis, linear motion platform coupled with a precision, commercial off-the-shelf (COTS) hexapod. This three-axis platform is referred to as the 3DOF XYZ stage. The design and capabilities of these systems are discussed throughout the paper.

The integrated positioning systems will allow the XRCF to successfully calibrate future space flight optics. Using its x-ray test capabilities, which were recently returned to service, the XRCF upgrades will permit calibration of larger diameter optics than were previously achievable. The expansive ranges of motion of the 1DOF transporter stage and 3DOF XYZ stage, combined with the precision positioning capabilities of their respective hexapods, will enable multiple sub-aperture measurements to be performed on x-ray mirrors with apertures larger than the facility's x-ray beam.

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2. BACKGROUND

The CoCOB hexapod, delivered in 2011, was originally designed by Moog CSA Engineering to support ground testing of the James Webb Space Telescope's primary mirror. The hexapod's precision positioning capability was used extensively in vacuum chamber testing at NASA Johnson Space Center as well as verification tests at NASA Marshall's XRCF. When the JWST testing concluded, XRCF personnel initiated discussions with Moog regarding the potential repurposing of the hexapod as a permanent element of its planned facility upgrade.

Repurposing of the CoCOB hexapod, as opposed to a rebuild or new development program, was justified for several reasons. The hexapod provided exceptional precision positioning performance for a large payload on JWST, and to the author's knowledge, all performance metrics remained at nominal levels at the conclusion of the testing. The design and workmanship had proven compatible with the high vacuum and optically clean environment needed in the XRCF chamber. Additionally, analysis demonstrated the hexapod had additional range of motion capability beyond what was needed for JWST, and because the original hexapod design was stiffness-driven, there was significantly higher load carrying capacity [2]. Unlocking these existing capabilities greatly expanded the range of test article sizes that could be accommodated. Repurposing the CoCOB hexapod also represented a significant cost savings, schedule reduction, and lower risk by using proven hardware.

3. SYSTEM OVERVIEW

For orientation, the XRCF system layout and coordinate system are shown in Figure 1. The x-ray beam first impacts the MAM test article which is supported and positioned by the MAM hexapod and 1DOF transporter stage. The focal plane instrumentation is aligned using the 3DOF XYZ stage and COTS hexapod on the far side of the test article relative to the beam source. The positive x-axis points towards the x-ray source, the negative z-axis is aligned with the gravity vector, and the y-axis is parallel to the width of the test bench.

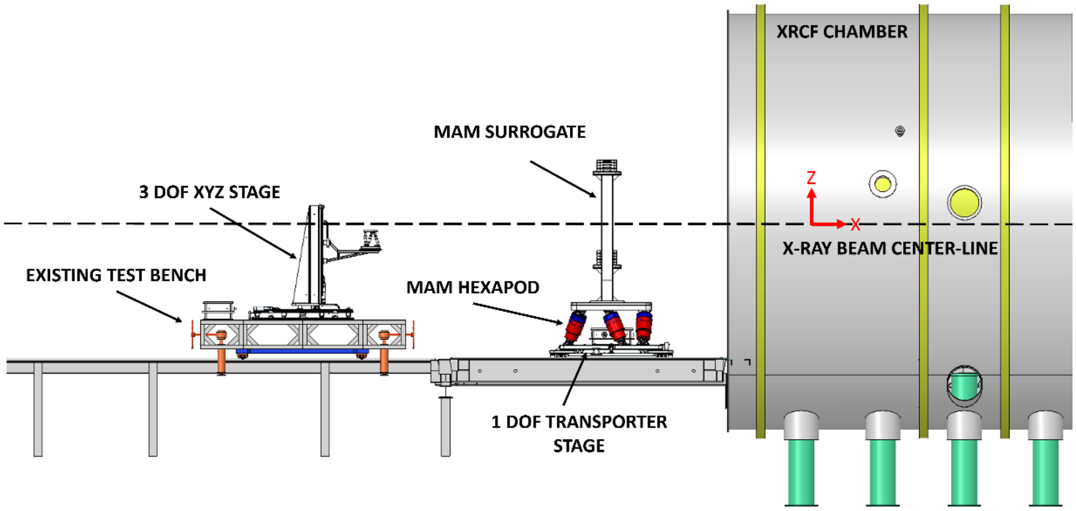


Figure 1. XRCF system layout and coordinate system

System requirements

The positioning requirements for the MAM hexapod, 1DOF transporter stage, and 3DOF XYZ stage are shown in Table 1. The MAM hexapod and 1DOF transporter stage work in conjunction to allow testing of very large optics. Both subsystems are required to handle payloads up to 4000 kg. The 1DOF transporter has an even higher load requirement to account for the mass of MAM hexapod which it must also support. While hexapods can precisely position a payload in all six degrees of freedom, their range of motion in any given axis is inherently limited to avoid self-collisions. The 1DOF transporter stage overcomes this limitation by providing long stroke travel in the y-axis across the entire usable width of the chamber. The minimum step size of the 1DOF transporter stage can be much larger since the hexapod can perform the fine adjustments.

Table 1. Positioning requirements for MAM hexapod, 1DOF transporter stage, and 3DOF XYZ stage

MAM Hexapod	**X-Axis**	**Y-Axis**	**Z-Axis**	**RX-Axis**	**RY-Axis**	**RZ-Axis**
Minimum Range	±95 mm	±95 mm	±80 mm	±2.5 deg	±2.5 deg	±5 deg
Minimum step size	2 µm	2 µm	2 µm	5 µrad	5 µrad	5 µrad
Repeatability	20 µm	20 µm	20 µm	10 µrad	10 µrad	15 µrad
Load	4000 kg	4000 kg	4000 kg	4000 kg	4000 kg	4000 kg

1DOF Transporter	**Y-Axis**
Minimum Range	±750 mm
Minimum step size	500 µm
Repeatability	5 µm
Load	5500 kg

3DOF XYZ Stage	**X-Axis**	**Y-Axis**	**Z-Axis**
Minimum Range	±500 mm	±1000 mm	±500 mm
Minimum step size	500 µm	500 µm	500 µm
Repeatability	15 µm	15 µm	15 µm
Load	300 kg	300 kg	100 kg

The 3DOF XYZ stage fills a similar complementary role with the COTS hexapod. It provides large ranges of motion in all three of its axes while the hexapod performs small alignment corrections. The focal plane instrumentation, typically a charge-coupled device (CCD) camera, positioned by these subsystems is relatively small and low mass compared to the MAM test article.

Mirror adapter module (MAM) hexapod and 1DOF transporter

The primary components of the MAM hexapod are the repurposed actuators and end-joints from the CoCOB hexapod. These brushless motor-driven, roller screw actuators and pre-loaded, tapered roller bearing-based end-joints offer several unique features [3] including fine positioning, high load capacity, and vacuum compatibility. The original CoCOB payload interface platform was replaced to meet the overall system height requirement and provide a larger payload interface surface with a more generic bolt pattern. The new payload interface platform is composite sandwich panel construction using aluminum facesheets and vented aluminum honeycomb core. The aluminum hexapod base plate was also redesigned to interface with the moving components of the 1DOF transporter stage on its bottom side.

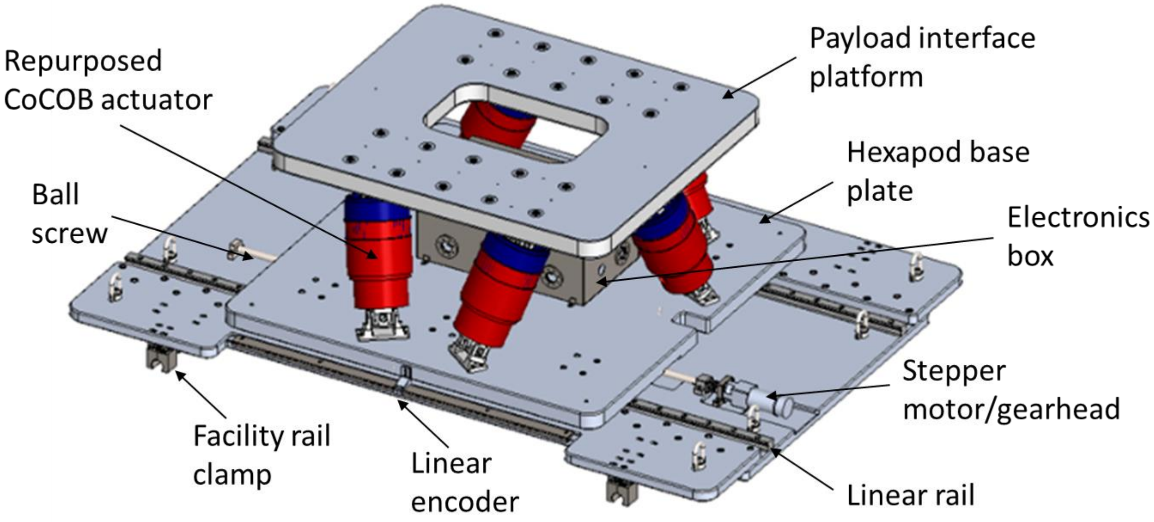


Figure 2. The MAM 6DOF hexapod system mounted on the 1DOF transporter stage

A 1DOF transporter stage was added beneath the MAM hexapod to provide the long-range motion in the y-axis. A stepper motor was chosen to drive the stage. A suitable vacuum-rated design was available without the need for customization, and the minimum step size requirement did not demand a higher precision option such as a brushless motor. An inline planetary gearhead with a 3:1 reduction ratio was paired with the stepper motor to achieve sufficient torque margins. A motor brake was included to ensure the stage would not backdrive. The motor/gearhead combination turned a ball screw which generated linear motion of a ball nut. A pair of linear rails with two carriages per rail supported the load and provided low friction guidance for the transporter stage. An absolute linear encoder, aligned along the length of the guide rails, supplied high resolution and high accuracy position feedback. With this linear encoder arrangement on the load, positioning errors resulting from backlash, windup, or linear compliance in the drivetrain, missed steps from the motor, and pitch imperfections in the ball screw can be eliminated [4]. A simple cable carrier system was installed along the 1DOF axis to provide cable management across the moving interface. Moog worked closely with each vendor and NASA personnel to ensure all components were suitable for the high vacuum, optically clean environment.

In addition to providing mounting interfaces to all the drivetrain and linear guide components on its top side, the aluminum base plate of the 1DOF transporter stage included roller bearing supports on its bottom side that interfaced to the linear rails of the XRCF facility. These linear rails allowed the combined 7DOF MAM positioning system to be easily slid in and out of the vacuum chamber. Rail clamps were also provided on the bottom of the base plate to allow the system to be locked in place on the facility rails.

An electronics enclosure holding all the power and drive electronics for the MAM hexapod and 1DOF transporter stage is located between the MAM hexapod actuators. Many of the components inside the enclosure are not vacuum-compatible. This requires the enclosure to be a sealed pressure vessel with a purge line running from the box to the wall of the vacuum chamber and maintaining atmospheric pressure within the enclosure. Provisions were included for providing forced air cooling through the box, but thermal modeling showed this to be unnecessary. This was later confirmed by test. Because the internals of the MAM hexapod actuators are also not rated for vacuum environments, corrugated pressure tubes port the actuator cables to the electronics box while maintaining atmospheric pressure inside the actuators and have the flexibility to accommodate small rotations of the actuators during operation.

3DOF XYZ stage

The 3DOF XYZ stage consists of three orthogonal linear axes. The three axes share a similar design architecture with each other and with the 1DOF transporter stage. All three axes and the 1DOF transporter stage use identical stepper motors, gearheads, motor brakes, and linear encoders which facilitates maintenance/troubleshooting and minimizes the number of spare components required.

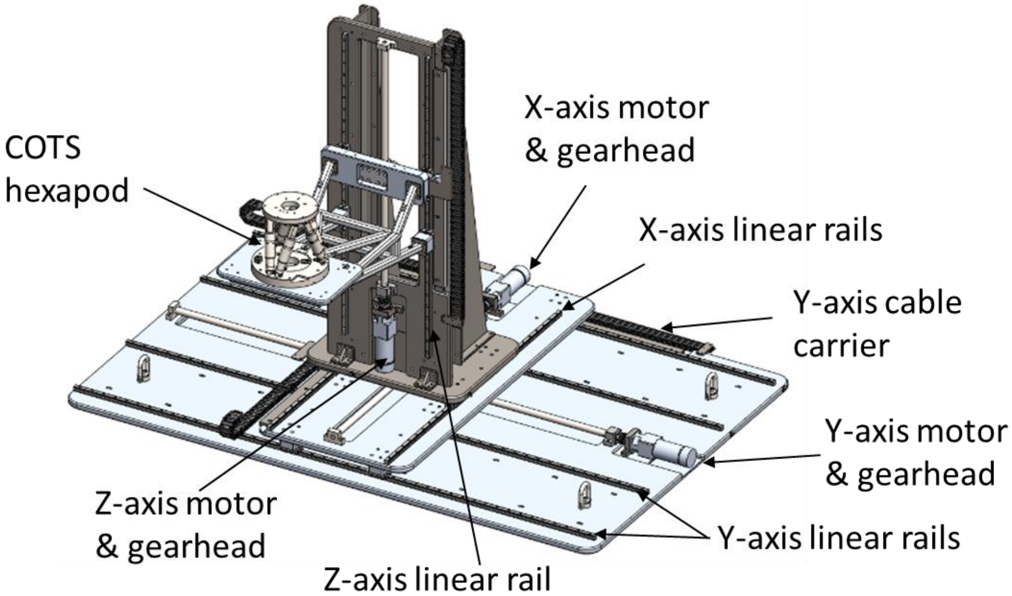


Figure 3. The 3DOF XYZ stage and 6DOF COTS hexapod

All three motion axes use the same family of ball screws and linear guides with the lengths modified as required. Due to the increased size of the of the y-axis stage, four linear rails are used on that axis while the x- and z-axes only require two linear rails each. Separate cable carriers are attached to each motion axis to manage the motor and feedback cables across the moving interfaces. Hard end stops are included on each axis to prevent overtravel in the event of a software malfunction. The three axes can move independently or simultaneously.

Similar to the MAM hexapod and 1DOF transporter electronics, the power and drive electronics of the 3DOF XYZ stage are housed within an enclosure located inside the chamber. The enclosure again serves as a pressure vessel to maintain the electronics at atmospheric pressure.

Improved system architecture and component upgrades

Since a goal of this program was to add additional motion systems, a significant effort was placed on upgrading the system architecture in a manner that both supported the legacy hardware and facilitated modernization. There were three main upgrades: 1) Ethernet for Control Automation Technology (EtherCAT), 2) modern operating system, 3) updated graphical user interface (GUI). These improvements will be the focus of the following sections.

EtherCAT

EtherCAT is a network-based topology that allows subsystems to be grouped and then wired together in a line or ring sequence. Moving to EtherCAT was a big architectural change, however, it facilitated enhancements that were paramount to the upgrade. First, since the DOF of the overall system were increasing from 6 to 16, an improved wiring and communication scheme was necessary. In the original CoCOB install, each of the motor/encoder cables were piped outside of the vacuum chamber to a control box. With the increased DOFs, the amount of additional wiring to maintain this approach was deemed excessive. The system schematic in Figure 4 displays the upgraded topology that significantly reduced the number of wires needing to exit the chamber but required the control boxes to be moved inside the chamber and become vacuum compatible. In general, this makes the system more modular and separable, offering greater flexibility. Additionally, since EtherCAT is a networked topology, multiple axes could be moved simultaneously and potentially coordinated.

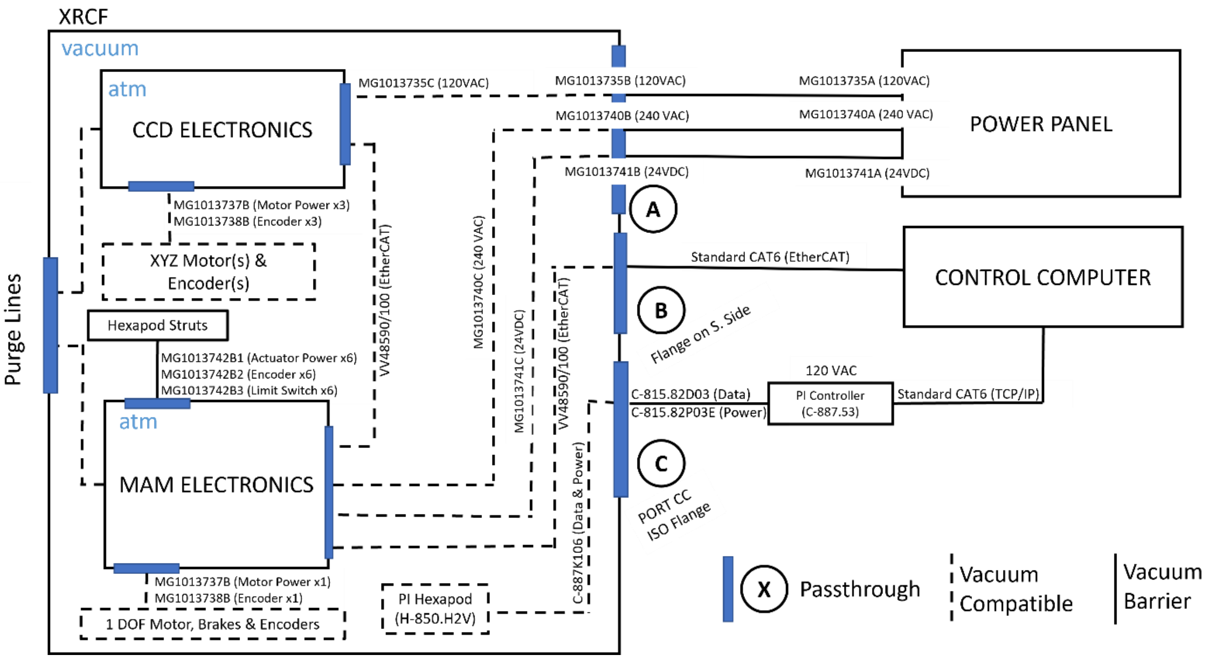


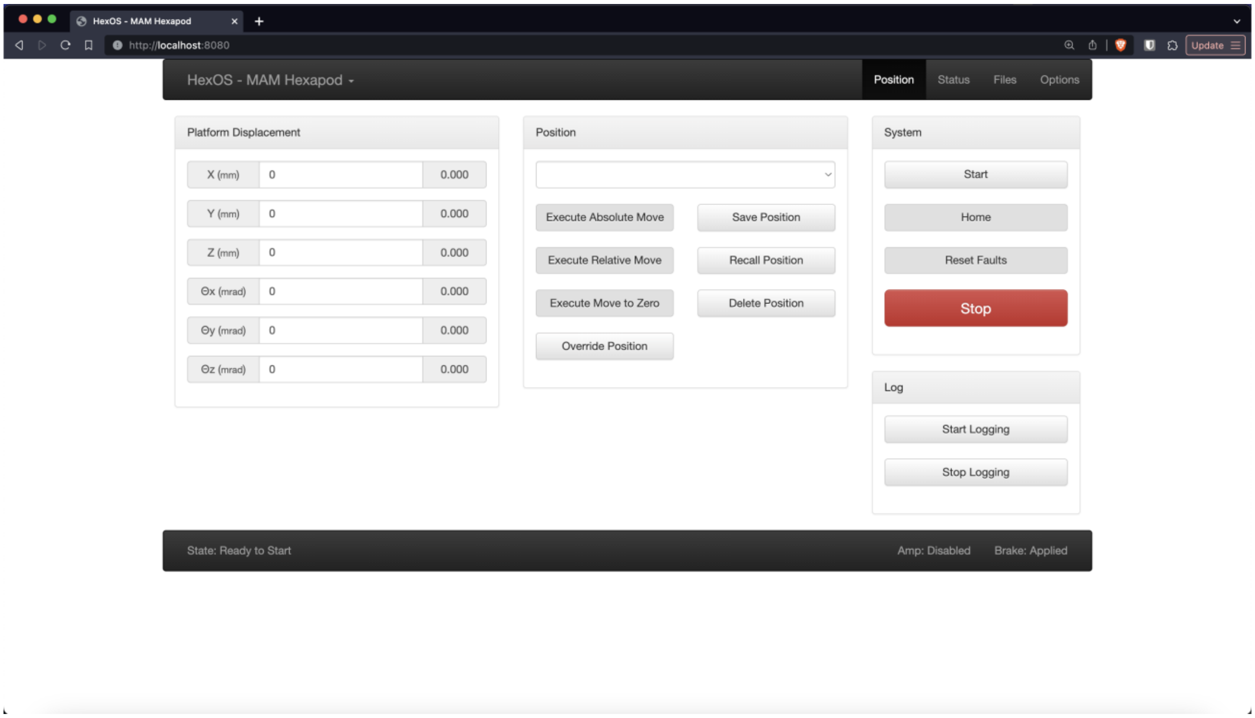
Figure 4. System Schematic

Modern operating system

As stated earlier, the original CoCOB system was deployed in 2011, and its Windows XP based operating system is no longer supported. Over the years, Moog has deployed several Linux + EtherCAT based systems, making this the logical choice for this upgrade. Linux is a very capable and configurable operating system, which allowed the system to include time synchronization, multiple network configuration, and remote access. The synchronization to a Network Time Server (NTS) allows the motion system's data to be correlated with NASA's other data streams. The extensible network configuration facilitated multiple benefits. First, it allowed the combination of multiple communication protocols, such as EtherCAT,and TCP/IP. Additionally, this flexibility allows the system to be operated or viewed from additional computers.

Graphical user interface (GUI)

Another goal of this system upgrade was to allow the operator control of the different motions stages via a single console. This was accomplished by providing a control interface through a web application. A sample of this interface can be seen in Figure 5. The web application supports the multiple motion stages by separating systems in browser tabs. This allowed each system to be modularly contained yet offer a consistent feel and operation. Additionally, since the control computer is network based, the control interfaces can be access locally or on any other networked computer, or even a combination of the two. This feature can also facilitate the transfer of system log files and data to different machines.



X (mm) 0 0.000
Y (mm) 0 0.000
Z (mm) 0 0.000
Θx (mrad) 0 0.000
Θy (mrad) 0 0.000
Θz (mrad) 0 0.000

State: Ready to Start
Amp: Disabled
Brake: Applied

Figure 5. Motion system control panel

The graphical user interface allows the user to execute absolute or relative commands, save and recall commonly used positions, home the system (hexapods only), restrict range limits, adjust velocities and accelerations, and change the pivot point/center of rotation (hexapods only). The GUI also provides status information including current state, actuator positions, motor currents, motor drive temperatures, motor brake status, and fault/warning conditions. Log files can be captured that include timestamped values for all key parameters and events.

4. SYSTEM PERFORMANCE

Mirror adapter module hexapod and 1DOF transporter performance

The measured performance parameters of the MAM hexapod are shown in Table 2. All tests were performed with a 4000 kg surrogate payload. It is important to note the ranges of motion of the six axes are interdependent. The listed values represent the maximum range with all other axes at their zero positions and the center of rotation located 1.480 m above the center of the payload interface. The rotational ranges about the X and Y axes (RX and RY) would increase significantly if the center of rotation was located closer to the payload interface. A Matlab-based tool was developed to quickly assess whether the hexapod can achieve any desired combination of motion in up to six axes with a specified center of rotation [2].

Table 2. MAM hexapod performance summary

	Range of Motion (+/-)	**Minimum Step Size**	**Repeatability (Uni-directional/Bi-directional)**
Translations:	mm	µm	µm
X	97.5	2	4.4 / 15.6
Y	103	2	2.0 / 11.4
Z	84	1	13.1 / 18.3
Rotations:	deg	µrad	µrad
RX	2.6	3	1.7 / 6.3

RY	2.6	2	2.0 / 7.0
RZ	5.2	2	2.2 / 14.0

The MAM hexapod demonstrated minimum step sizes of 1-2 µm and 2-3 µrad, and these values are consistent with the delivered performance of the CoCOB hexapod for JWST. Even smaller step sizes are achievable when commanding moves in the same direction or without requiring the actuators to change directions. Critically, the MAM hexapod never displayed highly undesirable behavior such as moving in the incorrect direction or lurching forward far beyond the commanded position. When the commanded step size was less than the minimum achievable step size listed in Table 2, the hexapod would move in the correct direction, but with a smaller magnitude than the commanded step. This type of behavior, which was typically only observed when changing direction compared to the previous move command, can much more readily be managed through tailored operating procedures.

Both uni-directional and bi-directional repeatability test performance is provided for the MAM hexapod in Table 2. Worst-case values measured during testing are reported, but the average repeatability values are significantly less. If the concept of operation allows for a specific position to consistently be approached from the same direction, the superior uni-directional repeatability performance can be realized.

Table 3. MAM 1DOF transporter stage performance summary

	Range of Motion (+/-)	**Minimum Step Size**	**Repeatability (Uni-directional/Bi-directional)**
Translations:	mm	µm	µm
Y	750	2	2.3 / 3.8

The MAM 1DOF transporter stage test performance is shown in Table 3. All tests were performed with a 4000 kg surrogate payload and the MAM hexapod installed. The ±750 mm range is much larger than what the MAM hexapod could provide to the test article on its own. The minimum step size of 2 µm is much smaller than required due to the use of high precision linear encoders and will reduce the amount of fine adjustment needed from the hexapod in that axis. The repeatability levels are very low both uni-directionally and bi-directionally. Most of the repeatability errors were attributed to hysteresis in the compliant pads used to level the system on the lab floor and should be improved with more rigid mounting.

3DOF XYZ stage performance

The 3DOF XYZ stage test performance is shown in Table 4. All tests were performed with an 80 kg surrogate payload. The ranges of motion are much larger than what the COTS hexapod could provide to the focal plane instrumentation on its own. Since the axes are independent, any combination of positions within those ranges can be reached simultaneously. The minimum step size of 2 µm in each axis is much smaller than required due to the use of high precision linear encoders and will again reduce the amount of fine adjustment needed from the hexapod in those axes. The uni-directional and bi-directional repeatability values are larger than the 1DOF transporter despite using identical sensors and drivetrain components. Similar to the 1DOF transporter, most of the repeatability errors were attributed to hysteresis in the compliant pads used to level the system on the lab floor. The structure of the 3DOF XYZ stage and measurement locations of the verification metrology amplified these effects more than the 1DOF transporter, but stiffer mounting in the XRCF chamber is expected to improve actual performance.

Table 4. 3DOF XYZ stage performance summary

	Range of Motion (+/-)	**Minimum Step Size**	**Repeatability (Uni-directional/Bi-directional)**
Translations:	mm	µm	µm
X	500	2	8.8 / 13.7
Y	1000	2	3.9 / 5.7
Z	500	2	10.2 / 7.5

5. CONCLUSION AND STATUS

A high-performance motion control system with a total of 16 degrees of freedom was designed, built, and tested that will greatly enhance the XRCF's capability to perform pre-flight verification of large diameter optics. The program produced a high precision, high load capacity hexapod with reduced cost, schedule, and risk through repurposing the actuators and end-joints of the CoCOB hexapod that was originally designed for the James Webb Space Telescope program. Additional 1DOF and 3DOF stages provided additional range of motion capability, met the requirements for the vacuum and optically clean environment, and included common design components to facilitate future system maintainability. Modern electronics, communication protocols, and graphical user interface provide flexibility to support future XRCF work. The test results demonstrate that all subsystems meet or exceed their requirements.

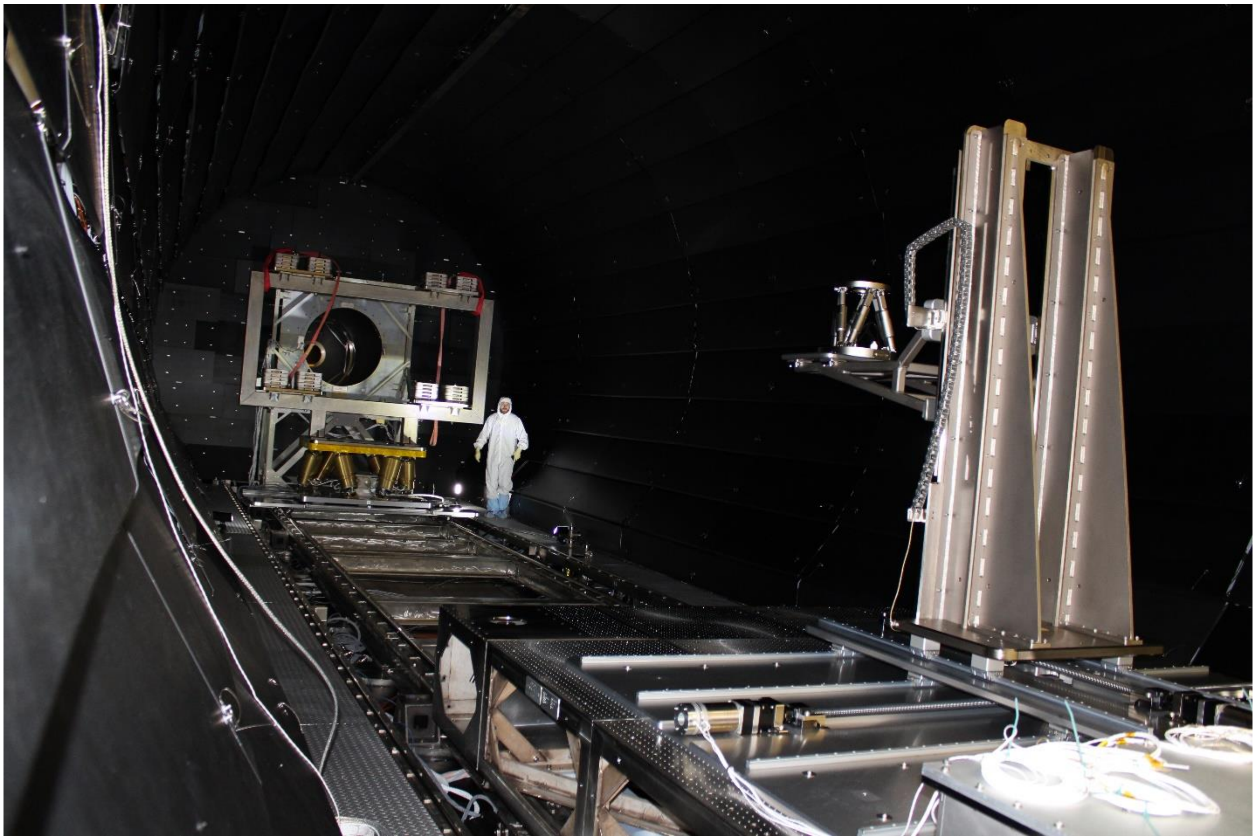


Figure 6. MAM hexapod, 1DOF transporter stage, 3DOF XYZ stage, and COTS hexapod successfully installed in the XRCF's vacuum chamber at NASA Marshall Space Flight Center

In February 2024, the MAM hexapod, 1DOF transporter stage, 3DOF XYZ stage, and COTS hexapod were all successfully installed in the XRCF's vacuum chamber at NASA Marshall Space Flight Center in Huntsville, Alabama. The final installation, shown in Figure 6, includes a 4000 kg surrogate payload installed on the MAM hexapod. Moog completed commissioning testing under vacuum conditions in April 2024 with all subsystems performing as designed.

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REFERENCES

[1] Jeff Kegley, William Abbot, Wayne Baumgartner, Gregory Daspit, William Hogue, Steve Johnson, Kristen Madsen, Mark Mimovich, James Tucker, Ernie Wright, "Capability improvements at Marshall Space Flight Center's x-ray and cryogenic facility," Proc. SPIE 12679, Optics for EUV, X-Ray, and Gamma-Ray Astronomy XI, 126790Y (2023) https://doi.org/10.1117/12.2678607

[2] Bryan Walter, Matt Granrud, Ryan Sneed, Mark Mimovich, Mark Welle, "Hexapod load and range of motion analysis for expanding optomechanical applications at NASA Marshall's x-ray & cryogenic facility," Proc. SPIE 13100, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation VI, (2024)

[3] Ryan Sneed, Michael Cash, Trevor Chambers, Paul Janzen, "Six degrees of freedom, sub-micrometer positioning system for secondary mirrors," Proc. SPIE 7733, Ground-based and Airborne Telescopes III, 77332R (2010) https://doi.org/10.1117/12.857793

[4] Ryan Sneed, Paul Keas, "Error reduction and modeling for hexapod positioners of secondary mirrors for large ground-based telescopes," Proc SPIE 9150, Modeling, Systems Engineering, and Project Management for Astronomy VI, 915020 (2014) https://doi.org/10.1117/12.2056644