TMT Primary Mirror segment actuators – from prototyping to production

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ABSTRACT

The Primary Mirror Control System (M1CS) of the Thirty Meter Telescope (TMT) incorporates 1476 precision electromechanical soft actuators that are used to perform closed-loop control of the 492 primary mirror segments in piston, tip and tilt. This paper describes the evolution of the M1CS actuator design from the early concept through several prototype rounds towards a design suitable for production at-scale. It offers insight into how TMT has and continues to meet the unique challenges and opportunities associated with manufacturing across an international partnership, in particular the need for high quality technical oversight and documentation at all stages of the process from prototype development, modeling, drawing production and subsequent assembly, test and verification. Key design decisions, refined through prototyping and testing to ensure optimum performance, reliability and serviceability are highlighted. Insight is given into the activities undertaken by TMT partners and vendors in India, especially as part of the vendor selection and vendor qualification that was undertaken as part of TMT's Production Qualification Phase (PQP) process.

Keywords: CELT, TMT, TIO, NSF, primary mirror, segment, actuator, prototyping, production.

1. INTRODUCTION

The Thirty Meter Telescope (TMT) International Observatory (TIO), formed in 2014, is an international scientific collaboration to design and deliver a thirty-meter class segmented-mirror telescope to the scientific community. It evolved from the California Extremely Large Telescope (CELT) project announced in October 2002 [1] and the TMT Observatory Corporation formed in 2003 [2].

This material is based upon work supported by the National Science Foundation under Cooperative Agreement No. 2331108.

Organization

TIO members are the California Institute of Technology, the University of California, the National Institutes of Natural Sciences of Japan, the Department of Science and Technology of India and the National Research Council of Canada. The Association of Universities for Research in Astronomy is an associate member, and major funding has been provided by the Gordon and Betty Moore Foundation. The National Science Foundation has provided funding for recent design and development work.

TMT in-house hardware-focused engineering capabilities are primarily in the Systems Engineering, Optics, and Controls groups. In general, lower-level hardware prototyping, fabrication, and small-scale manufacturing is carried out by contractors or other suppliers, often in partner countries.

In the TMT Work Breakdown Structure (WBS), the segment actuators are part of the overall M1CS system WBS element. Actuator design and development is carried out by the Jet Propulsion Laboratory (JPL) in Pasadena, California, and production of the resulting actuator design will be carried out by the India TMT Coordination Centre (ITCC), which is a coordinating organization consisting of three Indian institutes (Aryabhatta Research Institute for Observational Sciences (ARIES) in Nainital, the Indian Institute of Astrophysics (IIA) in Bangalore and the Inter-University Center for Astronomy and Astrophysics (IUCAA) in Pune).

2. OVERVIEW OF THE TMT OPTICAL SYSTEM

TMT is an altitude-over-azimuth (alt-az) mount telescope of a folded Ritchey-Chrétien design with three main optical elements – M1, M2 and M3 – directing the science beam to instruments on two Nasmyth platforms. The primary mirror, M1, is segmented with a 30 m aperture and a focal ratio of f/1. It consists of 492 individual irregular hexagonal segments of 82 different types, with typical corner-to-corner distances of 1.44 m. Each segment is supported within the M1 mirror cell, lying below the elevation axis, and while constrained in-plane each is able to be positioned in piston, tip and tilt (i.e. the three out-of-plane degrees of freedom) by the actuators described herein.

M2 is a 3.1 m diameter convex hyperboloidal mirror and is positioned by a hexapod with five degrees of freedom. It converts the f/1 beam from M1 into an f/15 beam for the science instruments.

M3 is a 3.5 × 2.5 m ellipsoidal flat mirror located above the center of M1 on an altitude-over-azimuth mount. It steers the incoming beam from M2 to any one of eight science instruments on the Nasmyth platforms.

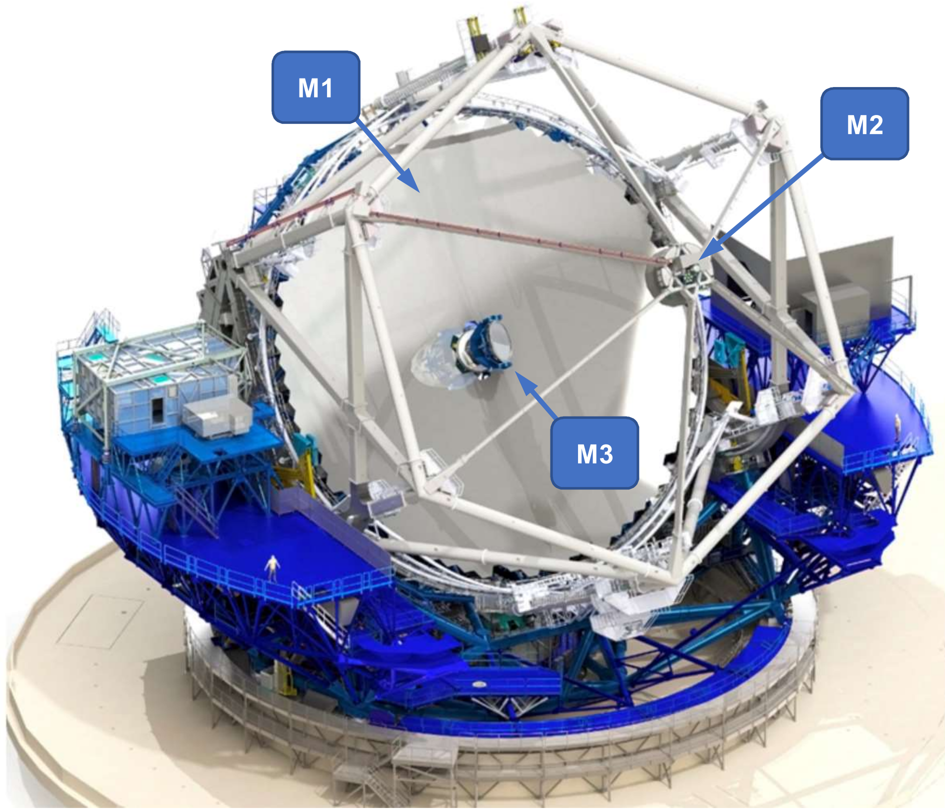


Figure 1 – A rendering of the Thirty Meter Telescope structure and the major optical elements

3. PRIMARY MIRROR CONTROL SYSTEM (M1CS)

The Primary Mirror Control System (M1CS) maintains the overall shape of the segmented primary mirror in the presence of structural deformations caused by temperature and gravity, and by disturbances from wind and vibrations (observatory-generated and seismic). It can be considered as a stabilization system, containing 1476 actuators and 2772 sensors, that maintains the shape of the primary mirror based on previously determined set-points. The Alignment and Phasing System (APS) uses starlight to make measurements from which the control set-points can be determined.

At each segment, three out-of-plane motions (piston, tip and tilt) are actively controlled by the M1CS via three precision actuators. Nanometer-level feedback of segment position relative to neighbouring segments is provided by two edge sensors per inter-segment edge, for a total of twelve sensors per segment, that measure height and gap. Sensor calibration, using the gap data, accounts for set-point variations attributable to changes in zenith angle and temperature. The M1CS also controls the surface figure of each segment using the segment active-optics warping harness system, based on measurements made by the APS. Control of segment figure is independent of the control of segment piston, tip and tilt.

M1CS segment actuator

Each M1 segment is positioned in piston, tip and tilt using three identical actuators that jointly act on each segment. Each actuator is attached to the fixed frame of the Segment Support Assembly (SSA) that supports the segment, and is the interface between it and the underlying mirror cell and telescope structure. The actuator output flexure is attached to the moving frame of the SSA, to which the mirror segment is attached. By controlling the positions (in piston) of the three actuator output flexures attached to the SSA at intervals of 120 degrees, it is possible to position the segment in three degrees of freedom.

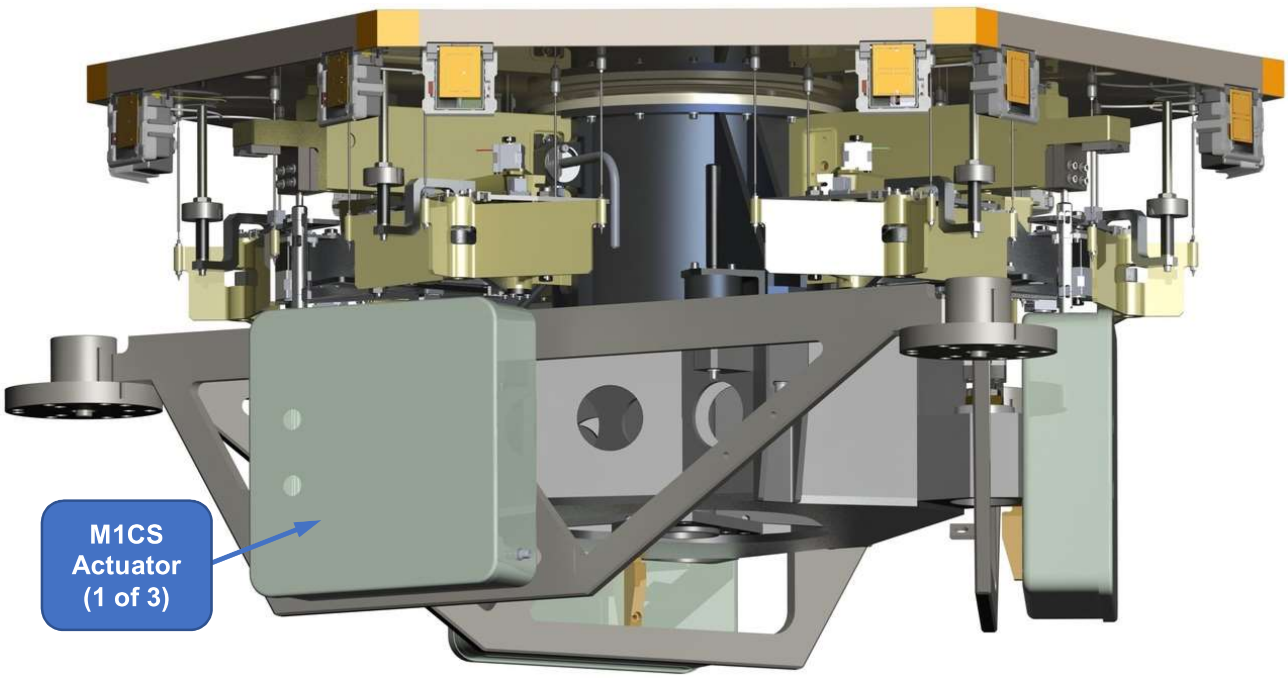


Figure 2 – Rendering of three M1CS P3 actuators installed in a Primary Segment Assembly (PSA)

Table 1 – M1CS actuator performance requirements

Requirement	Value
Power dissipation in operation (average)	1 W
Operational stroke range (minimum)	5 mm
Position slew rate (minimum)	30 µm/s
Force slew rate (minimum)	12 N/s
Position tracking rate (maximum)	260 nm/s
Force tracking rate (maximum)	0.066 N/s
Position tracking error (maximum, above 0.25 Hz)	4.4 nm RMS
Absolute tracking error (maximum, above 0.25 Hz)	50 nm
Axial stiffness (minimum, at DC)	20 N/µm
Axial load range (minimum)	0 to 850 N
Position loop control bandwidth (typical)	8 Hz. Limited by control-structure interaction effects with the telescope structure.

4. SEGMENT ACTUATOR DESIGN CONSIDERATIONS

The design of an actuator required to position an optical element in the presence of disturbances has been addressed in the aerospace and astronomical fields [3] since the early seventies at least. For astronomical applications, successful actuator implementations include the Keck telescope primary mirror segment actuators [4] and the Gemini Secondary Mirror Tilt System (M2TS) [5]. These two examples use significantly different approaches to achieve their performance requirements. In broad terms, the actuator designs may be characterized as either 'hard' or 'soft' types. Whichever type is chosen, the overall problem remains the same: to set and maintain the position of the actuator and its load in the presence of disturbances from various sources. In a ground-based astronomical observatory these disturbances typically arise from the effects of wind on the mirror(s), and vibrations (i.e. structural vibrations) from other sources (i.e. electro-mechanical sources such as drives, pumps, cryocoolers, fans etc., and potentially also seismic disturbances).

The hard actuator approach

A 'hard' or rigid actuator is one which has high intrinsic axial stiffness. It behaves like an adjustable but extremely stiff and rigid connection between the segment and its underlying support. In terms of maintaining position of the load in the presence of quasi-static forces such as gravity, this is ideal. But, the stiffness of the hard actuator at all frequencies means that it directly transfers forces between the segment and the supporting structure and vice-versa. This will promote the dynamic excitation of the local structure, and the high stiffness will result in low damping.

Control of the hard actuator is conceptually rather simple. In regimes where the external disturbances are minimal the intrinsic stiffness of the actuator can be relied upon to maintain position, and only intermittent adjustment may be required. The Keck primary mirror segment actuators are of this type. For application to TMT, such actuators would exhibit good wind rejection performance as their inherent stiffness resists wind disturbance, although the same property makes them less suited to rejection of structural vibration.

The soft actuator approach

A 'soft' actuator is one which has low intrinsic axial stiffness in the absence of some control action that actively provides it. For example, an actuator of this type may be based on a voice coil motor – the coil of wire surrounding a magnet in a conventional loudspeaker is almost identical in form and function. As an actuator, voice coils have several very desirable characteristics – they are non-contact devices, the force they produce is developed purely by the interaction of their magnetic fields, they can have relatively long stroke capability and they are entirely friction-free. Given suitable feedback and control, it is possible to design extremely precise, high-bandwidth actuators with high stroke and force capability, having high stiffness at low frequencies for position maintenance and lower stiffness at higher frequencies to limit vibration propagation. The Gemini secondary mirror actuators are of this type. In terms of the TMT, such actuators can achieve good rejection of structural vibration and wind disturbances, albeit at the cost of some design complexity associated with the control and the way in which quasi-static loads are to be supported.

5. M1CS ACTUATOR PROTOTYPES

Early actuator development activity

In 2005 TMT began to solicit for development of a high-performance actuator suitable for delivering piston, tip and tilt control of the telescope's 492 primary mirror segments; a total of twenty-organizations worldwide were contacted. The goal of this work was to develop an actuator design that met stringent positioning, slewing and disturbance rejection requirements while simultaneously meeting goals of low power consumption, low cost, simplicity, reliability and longevity. The work involved a selection of actuator candidates of various technologies, a prototyping, modeling, testing and down-select process, followed by a selection of an actuator technology which was subsequently developed through a series of prototypes into an actuator design. The prototype are currently (as of 2024) being produced by vendors in India.

Leading up to an actuator down-select activity in 2009, the following actuator designs were developed, and either prototypes or engineering models were fabricated. Below, 'Pn' refers to a particular prototype design ('P') and the appended number to its 'generation', i.e. P0 being a first-generation prototype, P1 a second-generation prototype and so on.

Table 2. Prototype and engineering model actuators developed for subsequent down-select

Item	Actuator	Category	Description	Developer/supplier
1	P0 Soft Actuator	Soft actuator	Voice coil soft actuator built for CELT.	Marjan Research
2	P1 Soft Actuator	Soft actuator	Voice coil soft actuator built for TMT. Offload via spring/pulley mechanism.	Marjan Research
3	P1+ Soft Actuator	Soft actuator	Voice coil soft actuator built for TMT. Offload via a spring/lever mechanism.	Marjan Research
4	Piezo Pump	Hard actuator (engineering model)	Hydraulic actuator that uses a piezo element as the active pump and magnetorheological fluid (MRF) as an actively controlled valve.	The Pilot Group
5	P1 Piezo Pump	Hard actuator	Same concept as (4) above, but with the MRF replaced with silicone oil and two valves.	The Pilot Group
6	P1 Piezo/Motor	Hard actuator	Uses a series combination of a motor-driven elliptical cam and a piezo element mounted in a mechanical scissor.	Jet Propulsion Laboratory

Each actuator candidate (prototype or engineering model) is briefly described below.

Marjan Research P0 Actuator

Marjan Research produced a P0 soft actuator early in the TMT's development, described in [3].

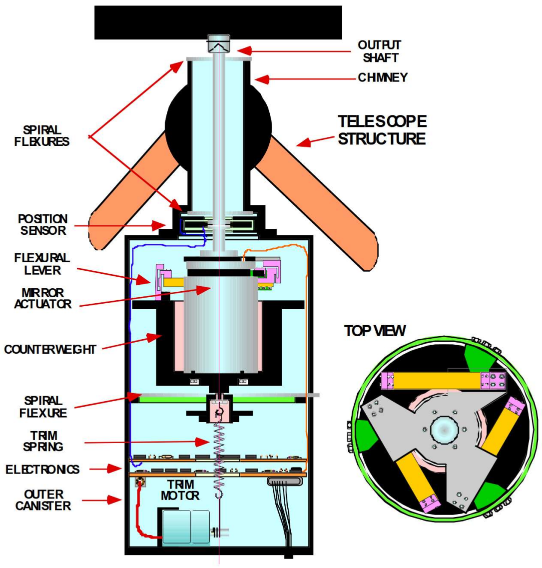


Figure 3 – The conceptual electromechanical design of the Marjan Research P0 prototype soft actuator

Figure 4 – Marjan Research P0 prototype soft actuator

Marjan Research P1 Actuator

Marjan Research further developed the P0 soft actuator design into their P1 prototype [6], while retaining the same fundamental design elements. It is again a soft actuator that develops force at the output flexure using a direct-drive voice-coil motor. A spring/pulley offloading system, driven by a stepper motor, is used to offload static load and thereby reduce the continuous power required of the voice coil. The position of the output shaft is monitored by an output position sensor and used to close a position loop which delivers the required stiffness. The linkage arm pivots are frictionless flexure bearings.

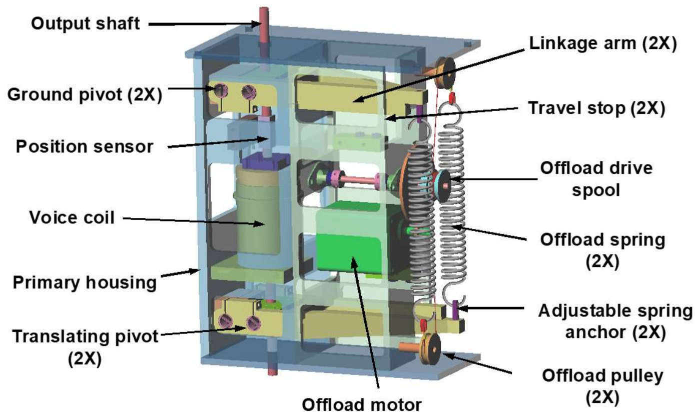


Figure 5 – Marjan Research P1 prototype soft actuator

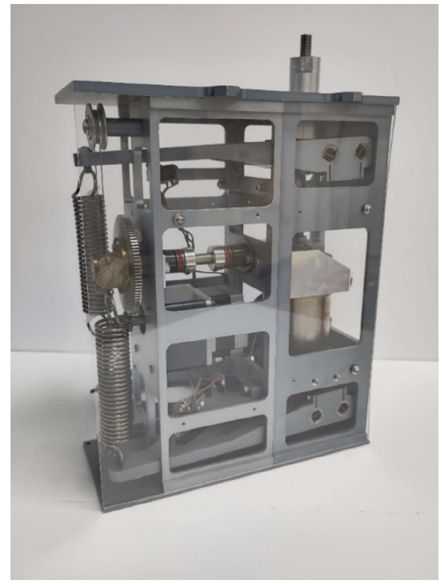


Figure 6 – Marjan Research P1 prototype soft actuator

Based on preliminary test results and an assessment of compliance to the more complete actuator design requirements, the P1 actuator design evolved into a P1+ ('P2 Proof-of-Concept') design that incorporated a number of improvements.

Marjan Research P1+ ('P2 Proof-of-Concept') Actuator

Marjan Research's P1+ design incorporated several changes from the P1 design:

- the voice coil was re-located to the far side of the lever for higher efficiency and to provide damping (for servo robustness) via voltage drive,
- a new offloader mechanism, using a commercially-available linear actuator driving die springs via a lever,
- mechanical changes to increase transverse stiffness, as well as the stiffness of other components,
- a reduction in part count.

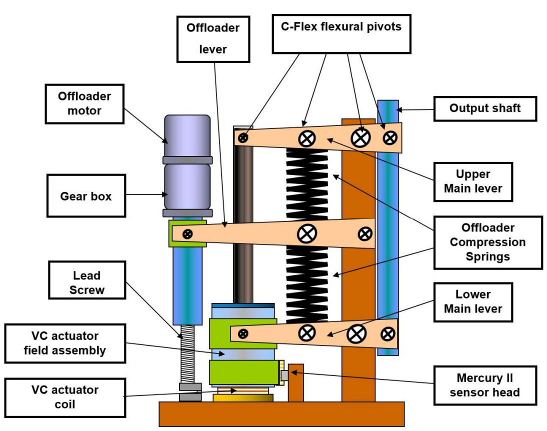


Figure 7 – Marjan Research P1+ soft actuator

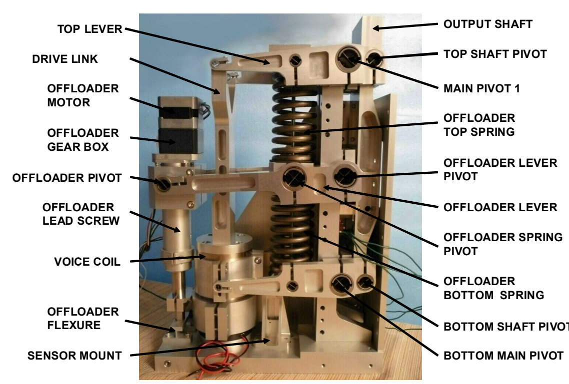


Figure 8 – Marjan Research P1+ soft actuator

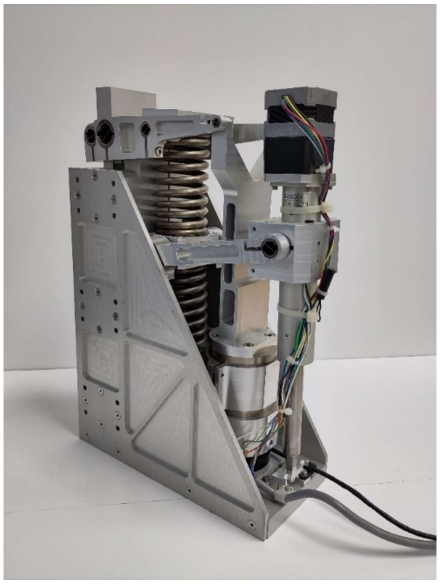


Figure 9 – Marjan Research P1+ soft actuator

Figure 10 – Marjan Research Segment Actuator Controller

The Pilot Group Piezo Pump Actuator

The Pilot Group (TPG), now part of the Re:Build group, developed a novel hard actuator prototype, firstly as an engineering model followed by a design revision incorporating some minor changes. The design drives an output shaft hydraulically, and uses a piezo-electrically driven pump to move fluid between the output actuator and a reservoir, with solenoid valves controlling the fluid path. A feedback loop is closed on the position of the output shaft as measured by a high resolution optical encoder.

The actuator is able to achieve the full range of output shaft translation required with a single mechanism. It has two distinct operating modes – continuous tracking, where the piezo-pump drives the position of the output shaft through a hydraulic reducer, and a fast-refill mode which operates when required, to add or remove fluid from the output actuator circuit at the extremes of the piezo-pump stroke.

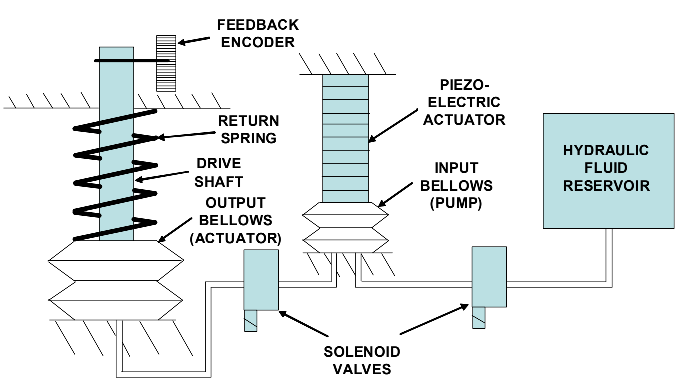


Figure 11 – Components of the TPG Piezo Pump hard actuator

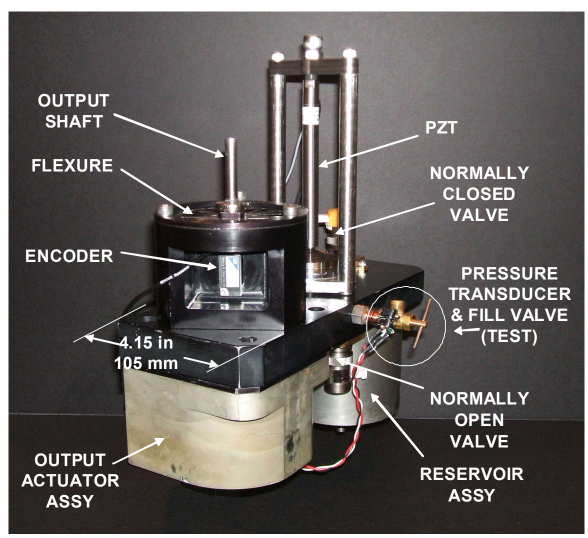


Figure 12 – TPG Piezo Pump hard actuator

Jet Propulsion Laboratory P1 Piezo/Motor Actuator

The Jet Propulsion Laboratory (JPL) also developed a hard actuator prototype for TMT. This design uses a piezo scissor stage to deliver fine control of the position of the output shaft. The mechanical scissor acts as a lever arm giving a multiplication of the change in length of the piezo element by a factor of two to three times. Output shaft position is read by a high resolution optical encoder which is used to close a position loop, and a stepper motor coupled with an eccentric cam is used to offload the mechanism at the extremes of travel of the piezo stage.

Like the TPG Piezo Pump actuator, this is a design that requires a periodic offloading process to occur during continuous tracking, as the travel limits of the piezo actuator are reached. This design has high intrinsic stiffness plus some damping provided by the source impedance of the drive amplifier[1].

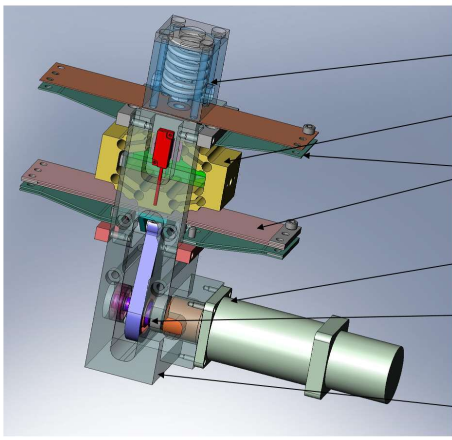


Figure 13 – JPL Conventional Technology P1 Piezo Motor actuator

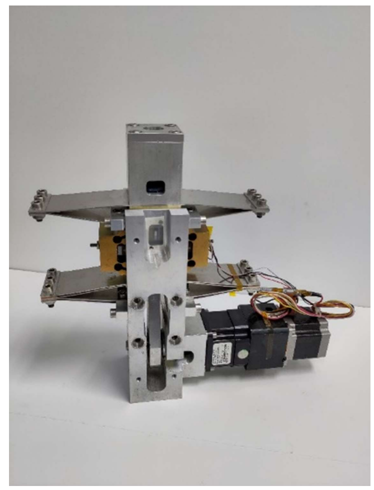


Figure 14 – JPL P1 Piezo Motor hard actuator

6. DOWN-SELECTION, DESIGN AND DEVELOPMENT

In September 2008 TMT reported on a trade study addressing the hard actuators, followed by the selection of one soft actuator design (Table 2, item 3), and two hard actuator designs (Table 2, items 5, 6) as candidates in a technology down-select process held in late 2009 [7]. The criteria for the down-select included:

- compliance with requirements, including accommodation of control-structure interaction (CSI) [8][9] for TMT's segmented mirror design,
- ability to meet nominal system dynamic performance. This criterion was affected both by low-frequency stiffness for wind rejection and high-frequency damping to minimize the impact of vibration,
- the impact of the design on the observing performance of the telescope,
- performance robustness against worst case disturbances, and considering various telescope models,
- assessment of reliability and risk associated with the design.

The highest-ranked approaches included some degree of damping, either intrinsically as with a soft actuator, or with active or passive damping applied to a hard actuator. At the conclusion of the technology selection, the recommendation was to proceed with a soft-actuator approach, as exemplified by the Marjan Research P1+ soft actuator (Table 2, item 3) with quasi-passive gravity offloading.

[1] With a resistive shunt, implemented as a series resistor to a voltage amplifier, the PZT gets stiffer at frequencies above the corner frequency set by the shunt resistor value and the PZT capacitance, e.g., transitioning from the short circuit to the open circuit boundary condition. Near the corner frequency, the transition in stiffness introduces damping.

In mid-2010 TMT began development of the P2 prototype soft actuator. This work built upon the design developed by Marjan Research in the P1+ and incorporated a housing design and mounting features for attachment to the fixed and moving frames of the SSA. Other changes included increasing the servo damping over the full range of travel, and ensuring that the actuator could accommodate anticipated earthquake loads, as discussed below.

TMT P2a actuator

P2a development began in June 2010 and incorporated the following features:

- a 'snubber' mechanism to limit instantaneous travel of the central four-bar linkage, which moves the output shaft, was added,
- a linear magnetic eddy-current damper was added to provide uniform damping over the full range of motion,
- a single-piece housing was developed which included the interface features needed for attachment to the telescope structure,
- the position feedback encoder was co-located with the voice coil actuator.[2]

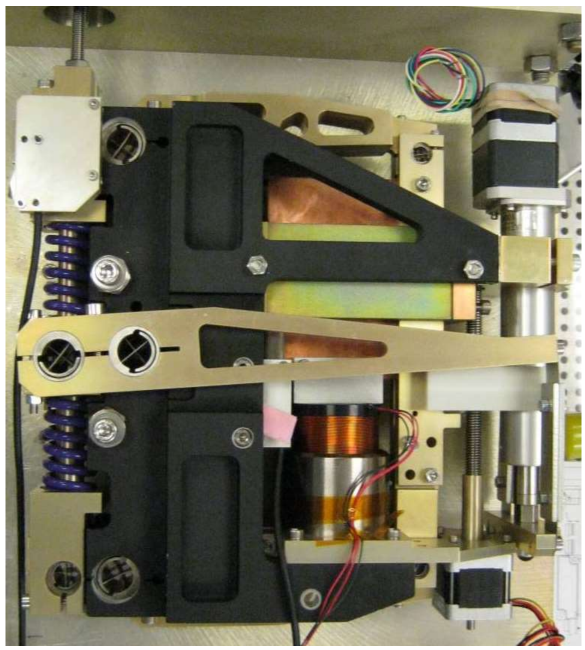


Figure 15 – A P2a prototype actuator

At this stage, many of the design features that persist into the current (P3) actuator design are present.

TMT P2b actuator

The P2b actuator substituted composite bearings in place of the rotational flexures in the offload arms. After testing, this change was adopted in the subsequent variants also.

Four actuators, consisting of P2a and P2b prototypes, were extensively tested in different configurations. These tests addressed lifetime and performance under different environmental conditions.

- lifetime tests – over multiples of the number of motion cycles anticipated in telescope operation,
- performance tests – to verify actuator performance over the full range of environmental conditions, both warm and cold.

[2] Ultimately, adequate co-location was demonstrated with an output-shaft encoder, and that approach was used for subsequent prototypes.

TMT P2c actuator

P2c actuator development began in late July, 2011 and was informed by lessons learned from the preceding P2 builds and the results of their testing. The intent of this revision was to prepare the actuator design for a trial build by TMT's Indian partners at ITCC, and subsequently undergo extensive testing in preparation for a preliminary design review.

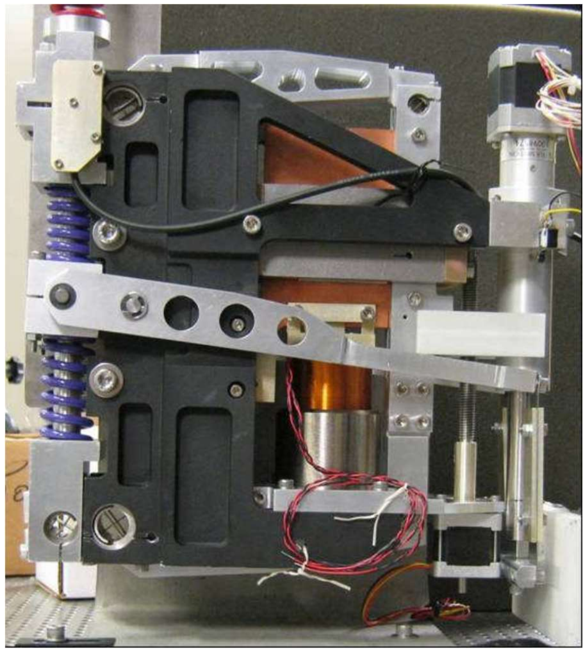


Figure 16 – A P2c prototype actuator

Tests performed included:

- verifying structural integrity,
- characterization of the snubber performance,
- a standalone seismic test,
- integrated seismic tests,
- lifetime tests,
- warm and cold standalone performance tests,
- dynamic testing on a prototype segment,
- integrated performance testing on a prototype segment.

TMT P2d actuator

A P2d design update was informed by lessons learned from the preceding P2c build and the results of the P2c testing, as well as feedback from the actuator preliminary design review held in 2013. This work began in April, 2014 and concluded a year later. Significant changes with respect to P2c were:

- improvements to the attachment methods used on the four-bar linkage,
- incorporation of a magnetic preload mechanism to improve performance at large zenith angles for actuators near the upper mirror boundary, which see a reduced gravity load,
- a modified offloader actuator with a separate thrust bearing,
- an improved output flexure with integral anti-buckling features,
- an improved snubber coupling.

Significant improvements were made to the drawing set, with fully dimensioned and toleranced drawings per GD&T specifications replacing the previous limited-dimension drawings..

TMT P2e actuator

The P2e actuator update was the result of preparations that needed to be made for a build round in India, which consisted of twenty actuators from four different vendors.

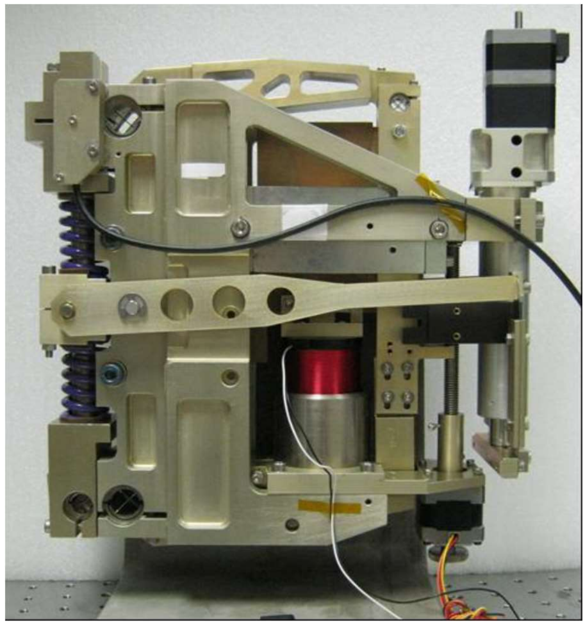


Figure 17 – A P2e prototype actuator

The P2e design included only small changes from the P2d, some of which were to allow for improved or simplified fabrication, assembly, and inspection.

In 2018 and 2019, samples of the twenty P2e actuators received from India underwent incoming inspection followed by lifetime testing, and warm and cold performance testing.

TMT P3 actuator

The current P3 actuator design is intended to be close to final. The main design changes were:

- a new magnetic eddy-current damper configuration was introduced which was significantly lighter, saving ~1 kg,
- the flexural connections between the ends of the offloader arms and the offloader linear actuator, which had been operating close to the fatigue limit of the material, were replaced by composite bearings,
- addition of absolute position sensors, using paired Hall-effect sensors to monitor the positions of the offloader and output shaft, plus an update to the earlier snubber Hall sensor design,
- a new, lower-power optical incremental encoder was incorporated.

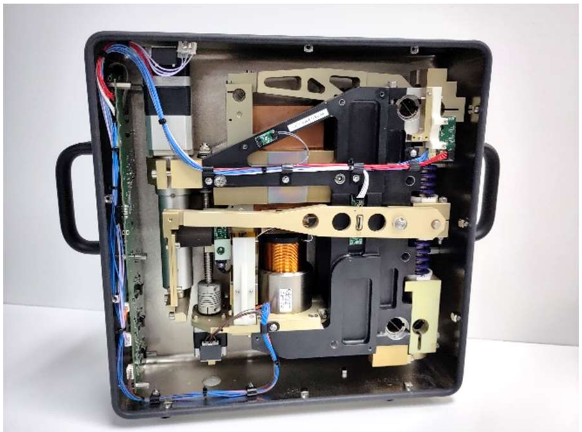


Figure 18 – P3 prototype actuator

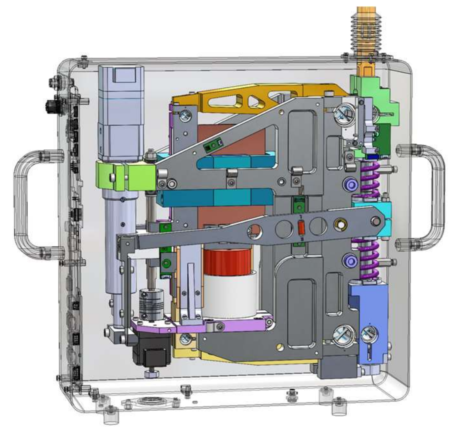


Figure 19 – P3 prototype actuator solid model

The main elements of the P3 actuator are highlighted below.

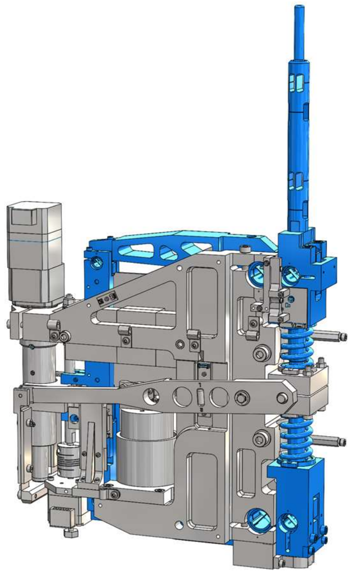


Figure 20 – The four-bar linkage chain

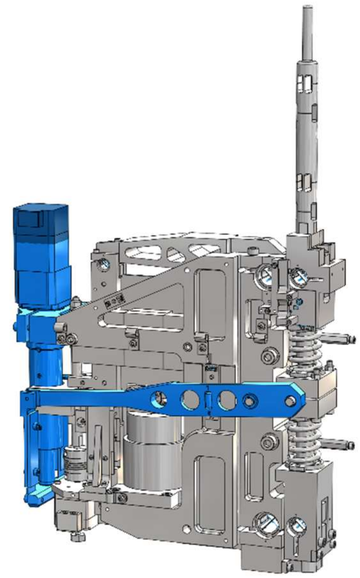


Figure 21 – Offloader actuator and offloader arms

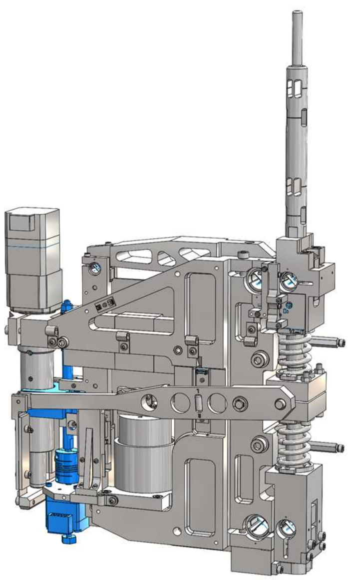


Figure 22 – Snubber assembly

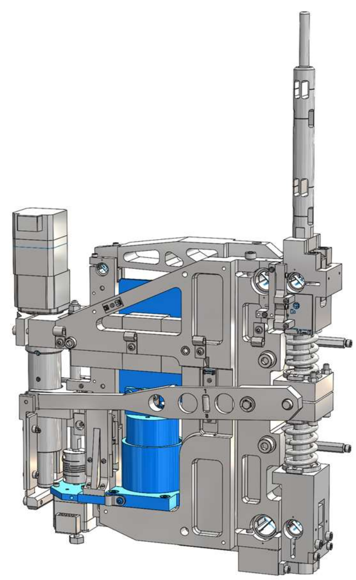


Figure 23 – Voice coil and magnetic damper assembly

The actuator enclosure design was completed in this phase. The enclosure is fabricated of deep-drawn aluminium 6061-T6 with an electrolytic nickel coating and is environmentally sealed to IP65. Two enclosure variants are produced, as each actuator comes in a ‘left-hand’ or ‘right-hand’ form which is needed accommodate installation constraints associated with the layout of the primary mirror cell. Purge air is supplied in order to maintain positive pressure within the actuator enclosure, and there are several access ports to allow installation and inspection as needed.

Installation, ergonomics and handling were carefully considered. An actuator in its enclosure and ready for installation weighs ~13 kg and is intended to be installed, removed and manipulated safely by a single person without additional handling equipment. Further, the output flexure, which will be fitted at this point and will protrude from the top of the actuator enclosure, must be protected from damage and must also not damage any other components accidentally, requiring that the telescope technician handling the unit must be able to hold and handle it easily. Another complication that was addressed was that it was not possible to lie the actuator stably on a flat surface due to the various external features – in particular, in the case of the back of the enclosure, the substantial mounting bracket. This drove the addition of feet to the bottom of the enclosure, which allows it to stand upright on a bench.

With the design of the actuator enclosure came the opportunity to finalize the location of the actuator controller electronics card. This card mounts to an enclosure sidewall and connects to the various electrical and electronic elements on the actuator as well as the external cable connector. Cabling runs and cable transitions between various parts of the actuator were defined and refined at this stage. There are several points at which cables have to transition across a moving boundary; at the voice coil, and the Snubber Hall Sensor board. These transitions are required to be low force, snag-free and highly reliable over the full range of mechanical motion and at any orientation of the actuator. A connectorized, guided flex-PCB scheme has proven effective.

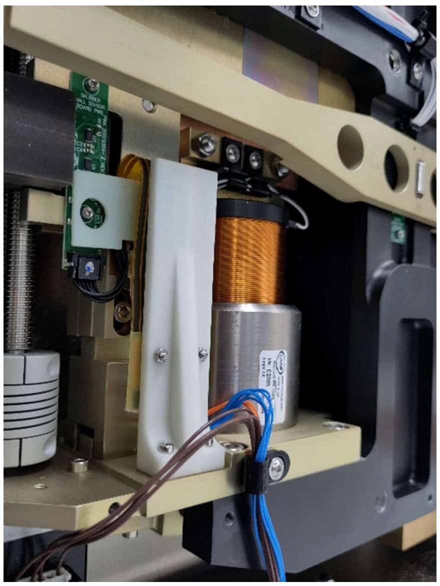


Figure 24 – A rigid bracket supports a flex-PCB carrying power and signal across a moving interface to the voice coil and snubber Hall sensor board

Figure 25 – Wire management and the transition between the voice coil wiring and the flex-PCB

The experience gained with initial P2e and P3 builds led to the development of numerous mechanical jigs being designed and made to support trouble-free, safe and consistent assembly and alignment. Jigs were made to support, amongst others,

- build up of the output shaft assembly, which uses large die springs in compression,
- assembly of the magnetic damper, which requires placement of powerful NdFeB magnets,
- alignment of the offloader arm attachment flexures during installation,
- installation and alignment of the C-Flex bearings.

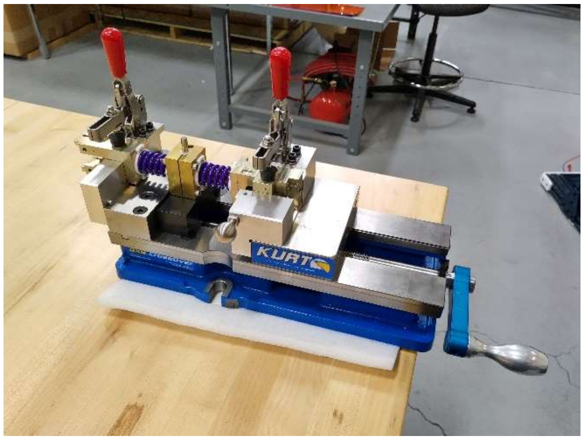


Figure 26 – Output shaft assembly jig

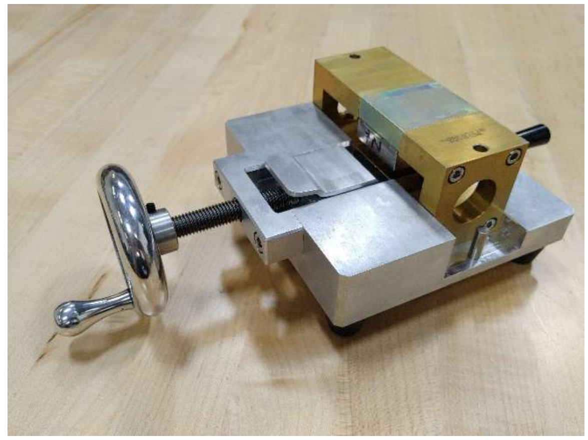


Figure 27 – Magnetic damper assembly jig

Figure 28 – Flexure installation jigs

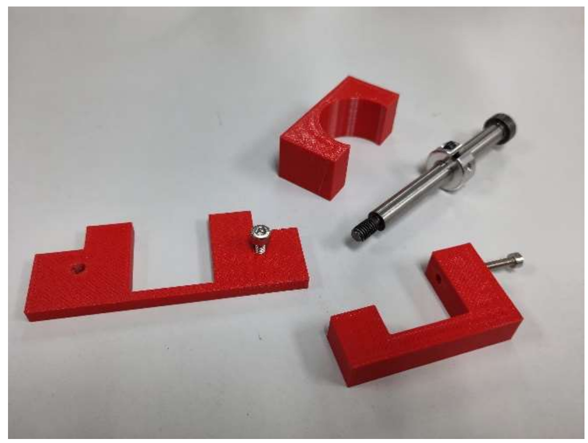


Figure 29 – Shipping restraint hardware

Provisions to properly restrain the actuator for shipping and transportation were also designed. Multiple restraint points where identified along with appropriate restraining hardware, which is installed following assembly and functional testing at the point that the individual actuator is being prepared for shipment.

7. SMALL-RUN MANUFACTURING

In 2017 TMT worked with ITCC to produce twenty P2e actuators in India. A Request for Proposal was released and seven Indian vendors responded expressing interest. Four vendors were subsequently qualified to perform the work, and purchase orders were placed for each of the four vendors to produce five actuators beginning in late 2017. All vendors completed their actuators in 2018. This initial run of actuator production was successful overall, and any discrepancies were able to be resolved by close cooperation between the vendors, ITCC and TMT teams.

In 2019, lifetime testing was performed on a selection of actuators at TMT's lab facility in Monrovia, California. This testing included of repetitive cycling of the actuator over its range of mechanical motion while in a temperature-controlled environment at room temperature and at -10 Celsius. As a result of the data provided by the vendors in their actuator End-Item Data Packages (EIDPs) and the subsequent environmental testing, all four vendors were qualified for future fabrication rounds, including full production.

For the P3 design, an initial set of three actuators was fabricated in-house in 2021 to validate the design changes. These were incorporated into a final P3 design package. In 2022, a limited-tender Request for Proposal was let by ITCC with the four pre-qualified vendors for the fabrication of twenty P3 actuators, with eighteen destined for TMT and two to remain with ITCC. Following a review of the responses, ITCC selected two vendors to perform the work and placed purchase orders with both, per guidelines laid down by the Government of India.

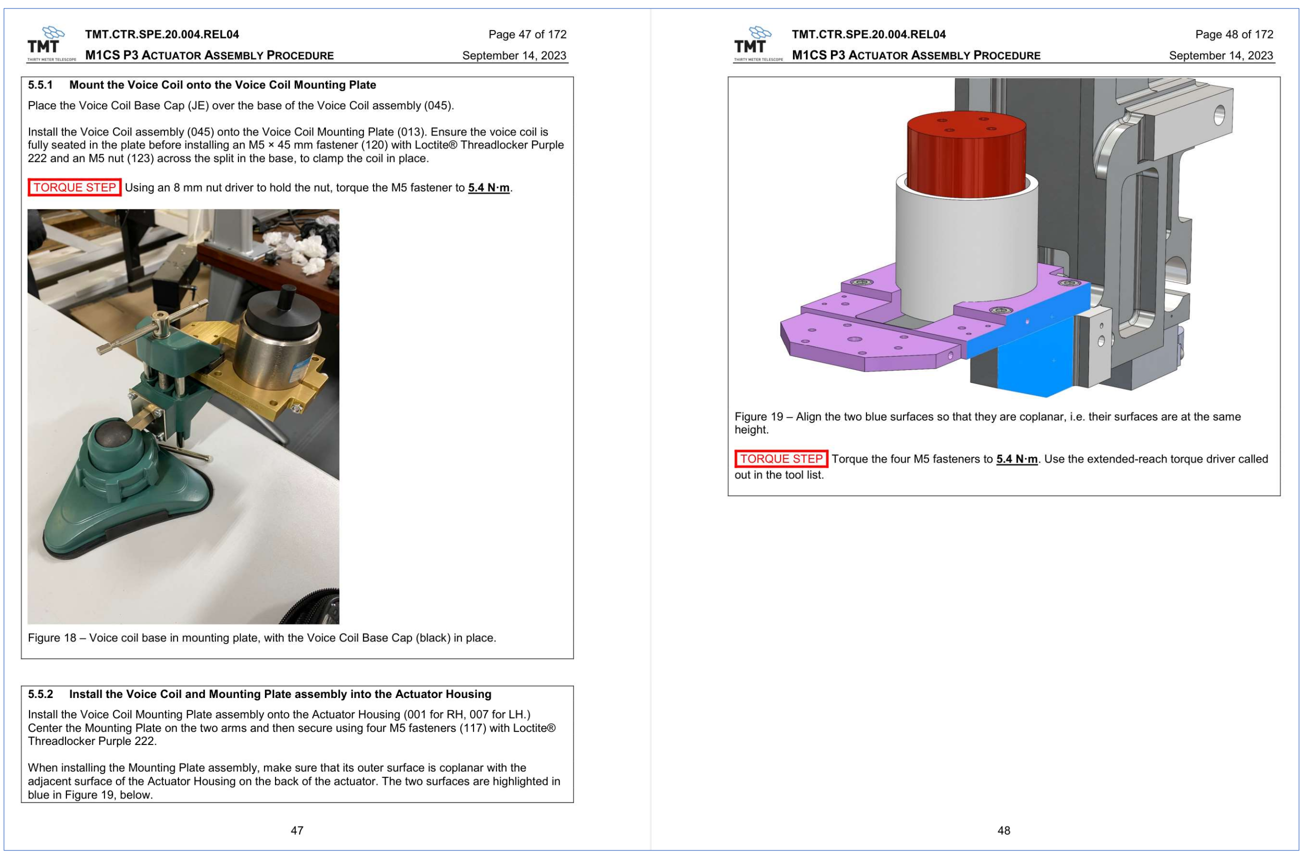
8. PRE-PRODUCTION MANUFACTURING

Assembly

During small-run in-house prototyping, the assembly of the actuators was performed by staff who had experience with earlier actuator versions and previous builds. Transitioning to larger-scale production, performed by external contractors, required the development of a more formal, comprehensive and detailed assembly procedure document. TMT developed this document bearing in mind that it must be:

- complete – every step needed in the assembly process is fully described and uniquely numbered,
- logical – at no step must the assembler be wondering why a particular step is called for,
- largely self-contained – the need to refer to external documents or sources of information is minimized,
- clear and unambiguous – descriptions and instructions must be unambiguous and accurate. Critical steps, such as torquing, and steps that have the possibility or risk of causing damage or operator injury are highlighted. The document makes extensive use of photographs taken during actual assembly and/or views generated from CAD models.

The document divides the assembly process into logical sections. Each begins with a list of tooling and components needed, as well as any assemblies completed in earlier sections that will be required for the current step. Once the entire procedure is completed per the document, the vendor will have an actuator ready for functional testing.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5.5.1 Mount the Voice Coil onto the Voice Coil Mounting Plate

Place the Voice Coil Base Cap (JE) over the base of the Voice Coil assembly (045).

Install the Voice Coil assembly (045) onto the Voice Coil Mounting Plate (013). Ensure the voice coil is fully seated in the plate before installing an M5 × 45 mm fastener (120) with Loctite® Threadlocker Purple 222 and an M5 nut (123) across the split in the base, to clamp the coil in place.

TORQUE STEP Using an 8 mm nut driver to hold the nut, torque the M5 fastener to **5.4 N·m**.

Figure 18 – Voice coil base in mounting plate, with the Voice Coil Base Cap (black) in place.

5.5.2 Install the Voice Coil and Mounting Plate assembly into the Actuator Housing

Install the Voice Coil Mounting Plate assembly onto the Actuator Housing (001 for RH, 007 for LH.) Center the Mounting Plate on the two arms and then secure using four M5 fasteners (117) with Loctite® Threadlocker Purple 222.

When installing the Mounting Plate assembly, make sure that its outer surface is coplanar with the adjacent surface of the Actuator Housing on the back of the actuator. The two surfaces are highlighted in blue in Figure 19, below.

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Figure 19 – Align the two blue surfaces so that they are coplanar, i.e. their surfaces are at the same height.

TORQUE STEP Torque the four M5 fasteners to **5.4 N·m**. Use the extended-reach torque driver called out in the tool list.

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Figure 30 – An excerpt from the P3 Actuator Assembly Procedure document

TMT maintains version control of the assembly documentation. Updates, additions and corrections are prepared based on feedback from vendors, testing and engineering activities and are captured in revisions to ensure that the documentation is kept up-to-date.

End-Item Data Package

Each actuator that the vendor delivers to TMT is required to be accompanied by a set of documentation to verify the compliance of the actuator with respect to the various build requirements, and the subsequent functional testing requirements. This set of documents, consisting largely of inspection and test reports, is termed the End-Item Data Package (EIDP) with one being delivered for each actuator.

Functional testing

Functional testing is designed to confirm that the actuator is operational to the level at which performance tests can be carried it. It addresses the following areas:

- actuator mechanism range-of-travel,
- position encoder functionality,
- voice coil motor force and output stiffness checks,
- snubber motor and Hall sensor tests,
- an open-loop damping test,
- the ability to read the actuator electronic ID.

An actuator is functionally tested immediately following assembly as part of the manufacturing process. This testing, completely specified by a functional test procedure developed and provided by TMT in the same manner as the assembly procedure, enables the vendor to perform a series of tests and checks on the actuator and document the results. The output of this testing will form part of the actuator EIDP. Functional testing in production will be the responsibility of the actuator vendor.

Performance testing

The final step for an actuator to complete is for it to pass a performance test. This is designed to demonstrate that the actuator meets its ultimate performance requirements and successful completion confirms that it is ready for installation in the telescope and subsequent use. TIO is currently performance-testing the P3 actuators as part of the P3 Actuator Qualification tasks. In future, performance testing in production will be the responsibility of the actuator vendor.

Performance testing addresses the following areas:

- position loop step response,
- slewing performance,
- tracking performance,
- identification of a SISO transfer function model of the actuator dynamic response (from the position demand input to the output shaft position encoder) over a defined frequency range.

9. PRODUCTION TIMELINE

Below is a summary of actuator production activities in India and the USA, starting in 2017.

2017

- a Request for Proposal was released for fabrication of P2e actuators,
- bids were received from seven Indian vendors showing interest in fabricating the P2e actuators,
- four vendors were qualified and considered for fabrication of actuators,
- Purchase Orders were placed in late 2017 for fabrication, assembly and testing of five actuators each, with all four vendors.

2018

- the vendors completed the fabrication and assembly of their actuators,

- any non-conformances on parts were resolved with support from ITCC and TIO,
- all actuators successfully passed functional testing.

2019

- lifetime testing of actuators was performed at TIO's Monrovia lab in California,
- based on the EIDP and test data, four vendors were qualified for the next round of fabrication including subsequent production,
- drawings updates were made based on the feedback from vendors, ITCC and testing performed by TIO,
- an in-house build of three P3 actuators commenced.

2020

- the P3 actuator drawing package was updated with feedback from the in-house build.

2021

- a limited-tender Request for Proposal was released by ITCC with the four vendors, for fabrication of twenty actuators (eighteen for TIO and two for ITCC),
- in December a purchase order was placed with two vendors, with a quantity split of twelve and eight actuators respectively, per Government of India procurement guidelines.

2023

- the fabrication and assembly of the first set of actuators was completed,
- factory acceptance testing of twelve of the actuators was completed,
- ITCC placed a purchase order for six additional actuators.

10. CONCLUSION

As of May 2024, the M1CS actuator work has reached what it considers to be the final pre-production prototype, P3. Samples of this actuator design have been produced in India as previously described, and have been received by TMT in Pasadena for further testing and evaluation. There is still a possibility for further small design changes to be made before the actuator design is presented at a future M1CS Actuator & Sensor Final Design Review.

The initial concept definition, supplier/contractor survey and early developmental rounds were successfully implemented with good results. The P2 development process, following the technology down-select process and building on the P1 prototypes, provided a solid baseline and substantial improvement at each design iteration. No show-stoppers have been identified, and the P3 design is anticipated to be able to meet the design requirements and perform as expected in the telescope over the lifetime of the facility.

Lessons learned

Undertaking any sort of development work of this type inevitably leads to useful realizations that will be helpful to others performing similar work in future.

It is worth taking the time and effort to produce and develop detailed procedures in support of the work, particularly in regard to assembly and testing. It was found that important knowledge and experience was sometimes not fully and effectively captured, and making an effort to do so made for significant improvements in the assembly documentation in particular, which in turn improved the ability of those assembling the actuators in an industrial environment to avoid mistakes and benefit from those with prior experience. The same applies to the actuator test procedure documentation, where again clarity and consistency is critical.

Long-duration projects that rely on personnel with specialized expertise and experience run the risk that inevitable departures will result in the remaining team losing valuable knowledge and skills. This can become acute if, for whatever reason, the project schedule extends beyond the likely availability of some team members. Transfers of knowledge, via documentation, working closely together, or even informal discussion is therefore vital. TMT has been fortunate in this respect to have had a closely collaborative relationship with the JPL team throughout, but especially in recent years as the P3 prototype has matured.

It is worth realistically assessing the effort necessary to successfully perform production, assembly and test of a sophisticated product such as the actuator by one or a combination of remote vendors. Initial discussions and facility visits by management are valuable during the initial contract enquiry and negotiation phases, but it was also found that it was invaluable to have a local TMT employee available in the vendor's region to act as a local representative. Properly resourced and empowered, this person can greatly assist the work by handling minor and/or local issues in a timely manner and ensuring effective escalation and communication between the vendors/contractors and TMT as the need arises.

It is likely that local vendors or contractors in other countries may in certain instances find it difficult or impossible to source items from a bill of materials supplied as part of a contract. In several cases TMT had to supply, on an ad hoc basis, items which for various reasons could not be obtained in India. In some cases this resulted in needing to alter the bill of materials to permit locally-obtainable alternatives, or to arrange for the necessary items to be purchased by TIO and shipped to the contractor directly.

The actuator development work required 'quick-turn' prototyping at various stages. Examples were electronics design for 'helper' tasks such as manual motor driving, making simple custom test equipment, making adapters, and machine-shop type tasks such as basic machining, shaping, milling etc. In some cases existing prototype parts had to be re-worked as issues were discovered, and the ability to carry out these tasks quickly was important. TMT was in many cases able to make good use of on-line fast-prototype houses, which are a fairly recent feature of the industrial landscape. Use was made of them for custom, small-run printed circuit board production for test equipment, various 3D printed plastic parts and simple machined metal components for assembly and jigging requirements throughout the actuator work.

Finally, with multiple parties involved world-wide, it should be emphasized that rigorous document and configuration control of drawings, procedures, design material and test results is essential.

Next steps

The P2/P3 prototyping process has delivered a suitable actuator design that has undergone only incremental changes, a reflection on the soundness of the chosen approach. Lifetime testing has identified a few minor and correctable issues. It has been possible to create a very detailed assembly procedure for the P3 actuator which has been successfully applied by the Indian contractors. Close collaboration with the Indian partners has resulted in timely and detailed feedback to TMT with corrections and suggestions to procedures and documentation. Having TMT's Multi-Segment Integration Testbed (MSIT) available has enabled 'form, fit and function' aspects of the actuator design to be verified early, especially in regard to the actuator enclosure, connectivity of services and interfacing to the Segment Support Assembly.

In general the actuator work has benefitted from the consistent and advantageous trend in price-performance in the semiconductor and encoder fields. Microcontrollers for embedded systems, and high resolution optical encoders suitable for embedded hardware are inexpensive, readily available and highly cost-effective. This has enabled the actuator to include both nanometer resolution position encoding and a complex embedded controller in the design.

The P3 prototype actuators that are currently being produced will be tested to both functional and performance levels in India and Pasadena and any minor changes identified as a result will inform the final design for production, which is intended to take place in India with supplier(s) identified during the prototype production stage.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the help and support of numerous colleagues and others within the TMT/TIO project and elsewhere who generously gave of their time and knowledge in support of the preparation of this paper. In particular, the authors would like to acknowledge the contributions of Dr. K. R. Lorell, whose insight and recollections of early actuator work for CELT, TMT and the Gemini observatory have greatly informed this paper, and Jim Moore for his work on the P2 actuator mechanical design.

The TMT International Observatory (TIO) gratefully acknowledges the support of the TIO Members and the Gordon and Betty Moore Foundation. The Members and their respective collaborating institutions are as follows: California Institute of Technology (Caltech); the National Research Council of Canada (NRC-CNRC); the Association of Canadian Universities for Research in Astronomy (ACURA); the Department of Science and Technology, Government of India (DST); the Department of Atomic Energy of India (DAE); the National Institute of Natural Sciences of Japan (NINS);

the National Astronomical Observatory of Japan (NAOJ); and the Regents of the University of California (UC). This work was supported as well by the Association of Universities for Research in Astronomy (AURA) and U.S. National Science Foundation (NSF).

Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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