PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Development status of the fast-steering secondary mirror of GMT

Sungho Lee, Jeong-Yeol Han, Ueejeong Jeong, Sanghyuk Kim, Bong-Kon Moon, et al.

Sungho Lee, Jeong-Yeol Han, Ueejeong Jeong, Sanghyuk Kim, Bong-Kon Moon, Chang-Hee Kim, Yunjong Kim, Chan Park, Byeong-Gon Park, Myung K. Cho, Christoph Dribusch, Youra Jun, Jieun Ryu, Gary Poczulp, Ming Liang, Il Kweon Moon, Chanhee Lee, Wongi Lee, Ho-Sang Kim, Paul Gardner, Robert Bernier, Frank Groark, Hugo Chiquito, "Development status of the fast-steering secondary mirror of GMT," Proc. SPIE 10700, Ground-based and Airborne Telescopes VII, 1070044 (6 July 2018); doi: 10.1117/12.2313174

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

Development status of the Fast-steering Secondary Mirror of GMT

Sungho Lee^{*a}, Jeong-Yeol Han^a, Ueejeong Jeong^a, Sanghyuk Kim^a, Bong-Kon Moon^a,
Chang-Hee Kim^a, Yunjong Kim^a, Chan Park^a, Byeong-Gon Park^a,
Myung K. Cho^b, Christoph Dribusch^c, Youra Jun^c, Jieun Ryu^c, Gary Poculp^b, Ming Liang^b,
Il Kweon Moon^d, Chanhee Lee^e, Wongi Lee^e, Ho-Sang Kim^e,
Paul Gardner^f, Robert Bernier^f, Frank Groark^f, Hugo Chiquito^f

^aKorea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea;

^bNational Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719, USA;

^cUniversity of Arizona, Tucson, AZ 85721, USA;

^dKorea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea;

^eInstitute for Advanced Engineering, Yongin-si, Gyeonggi-do 17180, Republic of Korea;

^fGMTO Corporation, 465 N. Halstead Street, Suite 250, Pasadena, CA 91107, USA

ABSTRACT

The Giant Magellan Telescope (GMT) will be equipped with two Gregorian secondary mirrors; a fast-steering secondary mirror (FSM) for seeing-limited operations and an adaptive secondary mirror (ASM) for adaptive optics observing modes. The FSM has an effective diameter of 3.2 m and is comprised of seven 1.1 m diameter circular segments, which are conjugated 1:1 to the seven 8.4m segments of the primary mirror. Each FSM segment has a tip-tilt capability for fast guiding to attenuate telescope wind shake and jitter. The FSM is mounted on a two-stage positioning system; a macro-cell that positions the entire FSM segments as an assembly and seven hexapod actuators that position and drive the individual FSM segments. In this paper, we present a technical overview of the FSM development status. More details in each area of development will be presented in other papers by the FSM team.

Keywords: extremely large telescope, Giant Magellan Telescope, Fast Steering Mirror, optics, opto-mechanics, mirror support, tip-tilt, image quality

1. INTRODUCTION

Secondary mirror of the Giant Magellan Telescope (GMT) consists of seven 1.05 meter segments, six off-axis and one on-axis, each forming an imaging pair with its corresponding primary mirror segment to achieve a common system focus. Two types of secondary mirror subsystems are provided: the Fast-steering Secondary Mirror Subsystem (FSMS) and the Adaptive Secondary Mirror Subsystem (ASMS). The FSM and ASM segments share a common optical prescription and a common interface with the secondary mirror (M2) Positioning System, which provides six-degrees-of-freedom motion for the seven segments relative to the telescope top end frame to compensate for thermal and gravity induced deflections of the telescope structure as shown in Figure 1. The M2 Positioning System is composed of seven short stroke, high precision hexapods called the M2 Segment Positioners for segment-to-segment motion and one large stroke hexapod called the M2 Global Positioner for positioning the common mounting frame for all seven segments. The FSM and ASM segments attach to the M2 Segment Positioners at a kinematic interface allowing the individual segments to be mounted in a repeatable manner.

Rigid mirror of each FSM segment is mounted in an individual FSM cell as shown in Figure 2. Three tip/tilt actuators provide pointing corrections at frequencies above the control bandwidth of the Telescope Mount^{[1][2]}. The main purpose of the FSM tip/tilt control is to mitigate image motion due to wind disturbances. The FSM tip/tilt actuators provide the precision required for image stacking in the focal plane. The FSM will be the commissioning secondary mirror for the GMT and will be used as well for regular operations when the ASM is off the telescope.

Figure 1: (Left) Integrated view of the GMT FSM Subsystem on the telescope top end frame. (Right) The blue hexapod under the telescope top end frame is the M2 Global Positioner and the yellow hexapods are the M2 Segment Positioners to which the FSM segments are mounted.

Figure 2: Structure and components of an FSM segment

Korean Giant Magellan Telescope Project (aka K-GMT Project) started in 2009 with the funding support from the Korean government. The funding included 10% share of the construction cost estimated at that time, support for the academic activities preparing for GMT era, and support for technology development regarding a secondary mirror of GMT. Main purpose of this technology development was to raise technological capabilities in Korea for the essential components in FSM by developing a full-scale prototype off-axis segment including cell and tip-tilt control mechanism. This FSM prototype (FSMP) project was conducted by the Korea Astronomy and Space Science Institute (KASI) and its collaborating institutions during the years 2009 and 2014^{[3][4][5][6]}. FSMP was not built from requirements and design provided by the GMT Organization (GMTO) which were not matured at that time, but KASI developed their own requirements and design for FSMP based on the same design concept for the real system, design of which was presented at the System Level Preliminary Design Review (SLPDR) of the GMT in 2014^[7].

Based on the MOU between GMTO and KASI for planning of the FSM subsystem, KASI conducted a project definition study funded by GMTO from November 2015 to February 2016. Goal of this study, which was called as a Phase 0 study for the FSM development, was a detailed planning of the FSM manufacturing, assembly, integration, and test (MAIT) including estimation of cost, schedule and risk management, etc. It also included a review of the FSMP project to identify which parts should be improved for the real system. The reports and review from the Phase 0 study^[8] were very useful to develop and improve the plan for next phases of the FSM development. The Phase 1 study of the FSM development, which is called as the delta PDR (dPDR) study since the PDR is regarded to have been held officially

as a part of the GMT SLPDR, was conducted from March 2017 to April 2018. The objective of the dPDR study is to complete the FSM design to a PDR level by incorporating the lessons learned during the FSMP development and suggestions from the Phase 0 study.

2. REQUIREMENTS

An FSM design is required to meet the requirements given in GMT-REQ-00508, FSM Design Requirements Document (DRD) and several interface control documents (ICDs) such as GMT-ICD-00188, the Mount Subsystem to FSM Subsystem ICD and GMT-ICD-01474, the M2 Positioner to FSM ICD. Also the requirements in the FSM DRD (GMT-REQ-00508) refer to several additional ICD documents. Table 1 lists these requirements and ICD documents by GMTO.

Table 1: FSM requirements and ICD documents

Document ID	Title
GMT-REQ-00508	FSM Design Requirements Document (DRD)
GMT-ICD-00188	Mount Subsystem to FSM Subsystem ICD
GMT-ICD-01474	M2 Positioner to FSM ICD
GMT-ICD-01705	Segment Handling System ICD
GMT-ICD-01707	FSM to Coating Chamber ICD
GMT-ICD-01380	FSM Metrology System
GMT-ICD-00596	FSM to Telescope Control System
GMT-ICD-01737	FSM to Telescope Metrology System
GMT-ICD-01735	FSM to Interlock and Safety System ICD
GMT-ICD-01736	FSM Device Control System Interface

2.1 Requirements and Specifications

A draft of the FSM DRD (GMT-REQ-00508) was available at the beginning of the Phase 1 study and a complete version of this document was released in July 2017. This version (Rev. A) of GMT-REQ-00508 has been revised from the draft but it still includes 19 requirements remaining to be further developed for clarification or completeness. Among the total number of 101 requirements, 32 requirements are for optical fabrication of mirrors which is out of scope of the Phase 1 study for opto-mechanical design and control system development; mirrors will be procured by GMTO separately. Table 2 lists the key requirements for the Phase 1 study from the FSM DRD.

From the GMTO requirements described above, the KASI team derived lower-level specifications for modeling, engineering, and planning for the FSM assembly development, which are fully described in KASI-TEL-REQ-10008. Among 111 specification items flowed down from the higher-level requirements, 12 items are TBD since their mother requirements need to be clarified, corrected or completed further.

Table 2: Key requirements for the FSM Phase 1 study

ID	Title	Requirement
GMT-FSM-47	FSM On-Axis Mirror Diameter	The FSM on-axis optic diameter shall be 1066.3 mm +/- 0.25 mm.
GMT-FSM-48	FSM Off-Axis Mirror Diameter	The FSM off-axis optic diameter shall be 1057.5 mm +/- 0.25 mm.
GMT-FSM-136	FSM Mass	The FSM mass shall be less than or equal to 225 kg.
GMT-FSM-14	FSM Tip-Tilt Range	The FSM tip-tilt mechanism shall have a range greater than or equal to 58 μ rad P-V per axis.
GMT-FSM-16	FSM Tip-Tilt Resolution	The FSM tip-tilt mechanism resolution shall be greater than or equal to 0.1 μ rad per axis.
GMT-FSM-86	FSM Tip-Tilt Dynamic Response	<p>The dynamics behavior of the secondary mirror segments shall be a low pass filter with a resonant pole and high damping as described by the equation:</p> $H_{fsm}(s) = \frac{4\pi^2 f^2}{s^2 + 4\pi\zeta fs + 4\pi^2 f^2}$ <p>where $s=j\omega$, the minimum frequency, f, is 25Hz and the minimum damping value, ζ, is 0.6.</p>
GMT-FSM-115	FSM Latency	The FSM system shall have a total latency of less than or equal to 0.2ms.
GMT-FSM-20	FSM Zenith Angle Range	The FSM shall meet its functional and performance specifications between Zenith angle 0° and Zenith angle 90°.
GMT-FSM-11	FSM Temperature Range	The FSM shall meet its performance requirements over the temperature range of -10 to 25 °C.
GMT-FSM-10	FSM Survival Level Earthquake	The FSM shall survive, without major structural failure, a maximum survival level earthquake (SLE) resulting in a maximum acceleration at the M2 Positioner - FSM interface of 4.2 g in the X-Y plane and 1.6 g in the Z axis.
GMT-FSM-8	FSM Operational Seismic	The FSM shall survive, with minimum consequential damage, and return to operations within 7 days of an operational level earthquake (OLE) leading to a maximum acceleration at the M2 Positioner - FSM interface of 3.1 g in the X-Y plane and 1.2 g in the Z axis.
GMT-FSM-109	FSM Heat Sources	The FSM segment assembly shall dissipate less than or equal to 25 watts to the surrounding air under normal (steady state) operating conditions.
GMT-FSM-100	FSM Service Lifetime	The FSM shall be designed for an operational lifetime no less than 20 years, with routine maintenance and periodic replacement of expendable components.

2.2 Interface Control Documents

One of the FSM ICDs, GMT-ICD-00188 (changed to GMT-ICD-01473), the Mount Subsystem to FSM Subsystem ICD was released in September 2017 while other ICDs have not been released yet but some information of interface requirements is available as drawings and drafts.

The GMT reference document, GMT-REF-01559, describes the M2 coordinate system (M2 CSYS). The origin of the M2 CSYS (i.e. M2 Mirror vertex) is located 20262.4761 mm above the primary mirror coordinate system (M1 CSYS) origin as defined in the GMT Optical Design Document (GMT-SE-DOC-00010). The primary axis of the M2 Mirror is the axis of revolution of M2, which is coincident with the Reference Optical Axis (ROA) of the telescope. Figure 3 shows the M2 CSYS of the seven optical surfaces of M2-S1 to M2-S7. Off-Axis Distance (OAD) is defined as the radial distance from ROA, therefore all six off-axis segments have the same OAD value (1087.7400 mm). Off-Axis Angle (OAA) is defined as the optical normal of each mirror segment at the OAD. OAA has been directly calculated as 14.777498° from the optical surface equation in conjunction with parameters defined in GMT-SE-DOC-00010.

Figure 3: M2 Coordinate systems, M2-S(1-7) CSYS

Design envelopes of the FSM segments are available in CAD forms as shown in Figure 4 for the off-axis segments.

Figure 4: Design envelope of an FSM off-axis segment

Locations and geometry of the kinematic mounts to the M2 Positioners, edge sensors and metrology fiducials are also available as CAD models. For edge sensors, a pair of the unit, a Launcher and a Receiver, are facing each other to monitor the positions so that relative motions of the segments are controlled. Spherically Mounted Retroreflectors (SMRs) for the metrology fiducials and the edge sensor Receivers are mounted at the front flange of the mirror while the Launchers are mounted on the side surface of the mirror blank.

2.3 Error Budget

The Natural Seeing Image Quality Error Budget (GMT-SE-REF-00145) describes requirements for GMT optical performance and top-level allocations of error budget, from which a sub-system error budget can be derived. Detailed error budget for the FSM design has been derived based on this document since the natural seeing observing modes is operated with FSM without using adaptive optics.

Figure 5 shows the FSM error budget. The basic structure is identical to the higher level error budget in GMT-SE-REF-00145. The elements that enter the budgets include fabrication errors in the optics and mirror support, misalignments and distortion due to the mounting of the optics in the mirror cell and dynamic motion of the mirror and thermal effects that contribute to image. Errors for mirror fabrication are assessed to be the realistic limit and the effect of wind is expected to be nearly negligible. Allocations for those error terms are the same as in the higher level budget. Thermal distortion budget is suggested to increase from 0.005 to 0.015 arcsec EE80 compared to the initial budget in GMT-SE-REF-00145. This assumes a worst case of temperature variation at the telescope site of $\Delta 30^\circ\text{C}$. Optical surface deformation due to a thermal soak of 1°C leads to increase of 0.5 nm in RMS surface error which corresponds to EE80 diameter contribution of 0.0005 arcsec. Additionally, dynamic effect on the optical surface deformation by tip-tilt acceleration is included for an extreme case of $60\text{ }\mu\text{m}$ P-V tip-tilt actuation (at the mirror edge) at 25 Hz frequency. The resulting EE80 diameter contribution at this condition is 0.018 arcsec. Allocation for M2 supports is slightly increased from the initial error budget based on a bottom up approach with performance prediction from engineering studies and experience gained with similar systems on existing telescopes. Also a reserve for margin of 0.005 arcsec is suggested considering environmental condition for testing in the laboratory. As a conclusion, the derived FSM error budget suggests a moderate increase of error allocation for FSM from 0.083 to 0.089 arcsec EE80.

Figure 5: FSM optical performance error budget

According to the FSM Optics Specifications Document, the FSM contributions to the overall goal of optical performance for GMT are relatively small. The reason is that seeing at the site is already 1.5 arcsec in 80% encircled energy (EE80) diameter. Especially, wavefront errors in a Gregorian telescope optics are dominated by M1, not M2.

Therefore, an increase in net M2 wavefront error of 20% or so would have only a negligible effect on the overall broadening of the system PSF produced by the telescope.

Also, it should be noted that the error budget in GMT-SE-REF-00145 is based on the seeing condition at the zenith, which is the most conservative criterion for determination of optical tolerances and support system requirements. Atmospheric turbulence increases the seeing-limited image size with zenith distance as $c \cos^{-3/5}(\text{zenith angle})$ in the Kolmogorov model. Therefore the specifications of maximum natural seeing image size are increased for off-zenith stellar objects by a factor of $\cos^{-3/5}(\text{zenith angle})$ but it is not reflected in the error budget.

Recently GMT-SE-DOC-00145 has been revised as the Natural Seeing and GLAO Image Quality Budgets. This revision incorporates additional error terms and reallocates errors in accordance with the most recent analysis, including the moderate increase of the FSM support error budget described above.

3. DESIGN

The FSM segment assembly mainly consists of mirror, support system and mirror cell. As shown in Figure 6, the sub-assembly components assembled on the mirror are axial support system, seismic restraint system, tangent bar, lateral support assembly, edge sensors and metrology fiducials.

The guiding philosophy for design of the GMT FSM is to minimize development and fabrication risks by adapting the legacy design from the Magellan Telescope M2 as described in the GMT telescope subsystem preliminary design report^[9]. The overall configuration of FSM is similar to that of the Magellan M2 which uses a lightweight mirror mounted by a combination of vacuum pressure and three axial piezo-electric actuators that provide fast tip-tilt motion. The lateral support of FSM is provided by a single flexure at the center of the mirror while the Magellan M2 is supported by three lateral supports.

In the dPDR study, detailed analysis and performance evaluations have been conducted to improve the PDR design considering lessons learned from the FSMP experiences. The lateral flexure design has been improved through an extensive trade study and parametric analysis. Designs of the breakaway system of the axial supports, the seismic restraint system and the tangent support have also been analyzed and their performances were evaluated which had not been fully investigated by the GMT SLPDR. In addition, the vacuum support system and sealing locations have been redesigned to improve the system performances and to accommodate the interfaces with the edge sensors and the metrology fiducials.

In this section, we summarize the main design features which have been improved through the dPDR study. More details on the FSM design are described in our separate papers by Cho et al. (2018)^[10] and Jeong et al. (2018)^[11].

Figure 6: (Left) FSM segment assembly in a sectional view. (Right) Sub-assembly components on the FSM mirror.

3.1 Mirror Design

The FSM segment contains a meniscus concave mirror. The central segment has an on-axis mirror with a physical diameter of 1066.3 mm and a clear aperture of 1050.3 mm. Six off-axis mirrors have a physical diameter of 1057.5 mm with a clear aperture of 1041.5 mm. Each segment consists of an array of hexagonal lightweight patterns with a wall thickness of 5 mm. The diameter of the central hole for the lateral support has been increased from 100 mm to 150 mm to enhance the stiffness of the lateral support tube against bending by gravity or wind shake as well as to accommodate a new design of the lateral flexure (see Section 3.2).

To evaluate the performance of the mirror model, detailed finite element (FE) analyses have been conducted under a variety of loading conditions such as gravity, temperature, and vacuum pressure. Sensitivity analyses regarding supports misalignments, vacuum sealing force and additional lateral force were also examined. Optical performances are assessed in terms of arcsec of the encircled energy at an 80 % diameter (EE80). The FE model assumes a solid concave lightweight mirror with a thickness of 120 mm and a mass of approximately 90 kg. The mirror is assumed to be made of Zerodur™ with a coefficient of thermal expansion (CTE) of 20×10^{-9} m/m/°C. The optical surface of the mirror is defined with a radius of curvature of 4163.901 mm and a conic constant of -0.7169273 which were basically generated from the optical design software Zemax™. A lateral flexure model with a central diaphragm of 0.4 mm thick is also included in the FE model as connected to the mirror at the center of gravity (CG) location (see Figure 7). Addition to this, a vacuum pressure is applied to balance the mirror mass in the FE analysis. The mirror cell is pressurized to balance the mirror gravity during telescope operation in the FSM design concept. The balance between gravity and pressure is achieved by vacuum pressure control with feedback from the load cells in the axial supports.

Figure 7: FE model of the FSM mirror; isometric view of mirror and constraints.

The mirror model shows natural frequencies of higher than 567 Hz. Mechanical deformation of the mirror has been further investigated against self-weighting loads of axial gravity and lateral gravity, and thermal loads of temperature soak and 1 °C temperature gradient across the mirror thickness. Impact by such a mirror deformation on the optical performance in EE80 ranges from 0.0004 to 0.014 arcsec for the on-axis mirror and from 0.0004 to 0.021 arcsec for the off-axis mirrors, with piston, tilt and focus removed, respectively. Deformation of the mirror surface in its dynamic motion of tip-tilt has also been assessed. An extreme condition of a sinusoidal motion of the maximum stroke (± 6 arcsec tip-tilt) at the maximum frequency (25 Hz) can cause a degradation of the optical performance by up to 0.009 arcsec EE80 which is well within the error budget.

To evaluate the safety level for the mirrors, Von-Mises stress of the flexure and shear and peel off stress of the bonding have been calculated as well. Detailed results are presented in Cho et al. (2018)^[10] from which one can find the stress level is well below than the level of possible handling stress. Also this FE model has been used for sensitivity analyses in the development of error budget, such as mis-positioning of the lateral flexure from the CG location of the mirror, residual error of the vacuum pressure control, and pressing force on the mirror by the vacuum sealing. In addition, heating effect by the tip-tilt actuators and the load cells has been calculated by a heat transfer analysis to examine any thermal distortion of the mirror surface which is only 0.0001 arcsec in EE80.

3.2 Mirror Supports Design

The FSM support systems are designed to accommodate lateral components of gravity solely by the lateral support and axial components of gravity solely by the axial supports including the vacuum pressure support. The lateral support assembly consists of a lateral support flexure, a lateral support guide rod, an axial adjustment tube, and a clamp. The lateral flexure is mounted at the central pocket of the mirror. It is designed to take loads only in the lateral direction and flexible in the axial direction. In the horizon pointing load case, the weight of the mirror is entirely supported by the lateral flexure. We have explored several design variations for the lateral flexure using FE analysis and selected the

design shown in Figure 8 based on the merits between stiffness and thermal compliance, prior experiences, and lessons learned from existing telescope projects. The lateral flexure is modelled as bonded to the mirror using epoxy 3M-2216 with a bond-line thickness of 250 μm on 12 bonding pads in total (two pads for each EDM part). The lateral flexure has been analyzed to determine its properties and optimize the design. The analyses included static gravity loading, nonlinear behaviors, thermal effects, and buckling analysis. More detailed design and analysis of the lateral flexure are addressed in Cho et al. (2018)^[10].

Figure 8: Assembled view (left) and exploded view (right) of the lateral flexure.

When dynamic stabilities of the lateral flexure FE model were explored, we found an insufficient rotational stability due to the diaphragm disk while the six radial flexures were stiff enough. This lack of torsional stiffness can be improved by introducing a tangent support. The tangent support is mounted near the outer edge of the FSM mirror. It is connected to the cell on one side and to the mirror on the other side as shown in Figure 9. The tangent support constrains the rotation about the local z axis. After a trade study of comparing with a slender rod type bar which was used for the Magellan M3 mirror, the design of a stack of two PI P-176.60 flexible tip flexures has been selected for FSM.

The axial supports constrain three degrees-of-freedom: tip, tilt, and piston (local z axis). Each axial support consists of the following key components: 1) a breakaway clamp assembly for seismic overload protection, 2) a PI P-845.30 PZT actuator, 3) two PI P-176.60 flexible tip flexures to accommodate tip-tilt motion, 4) a 1010-AF-5K load cell, and 5) preload springs to keep the PZT actuator in compression (see Figure 10). Among the four types of PI P-845 piezo actuators, P-845.30 was selected for the FSM actuators considering the travel range and resolution requirements.

The axial support assembly includes a feature to limit the force exerting mirror as a safety mechanism, called the breakaway system (BAS). This system inhibits positive and negative axial motion of the mirror with preloaded springs, which limit the maximum forces exerted on the mirror and thus reduce the likelihood of damaging the mirror in case of an earthquake or similar event. Behavior of the BAS model has been demonstrated by a dynamic simulation as well as an experimental test using a single BAS assembly from FSMP which is fully described by Kim et al. (2018)^[12]. The test results indicated that the system worked adequately when excessive loads are applied and implied that preload spring lengths should be carefully dialed during fabrication and assembly. Also, behavior of mirror stresses during the BAS operation has been analyzed by a study of high fidelity integrated modeling to understand how stresses are transferred to and from the mirror under various loading conditions. The maximum principle stress is expected to be 0.73 MPa, which is far below the maximum allowable stress.

Figure 9: Tangent support mounted on the cell and on the back surface of the mirror.

Figure 10: Axial support assembly (left) and the breakaway system (right).

To prevent excessive loading on the axial and lateral mirror supports during a seismic event or rough handling during AIT or shipping, three seismic restraints are included in the FSM segment. The restraints are located in three places at 120 degrees apart on the back side of the mirror avoiding the axial support locations. This feature is designed for excessive loads larger than the preload force on the breakaway system of the axial support, and up to the maximum accelerations anticipated for a survival level earthquake at top end of the telescope which is 4.2 g in X and Y axes, and 1.6 g along Z-axis. An FE model for the seismic restraint has been created with an appropriate trade-off between computational efficiency and accuracy. Instead of meshing the whole mirror, only a ring of Zerodur surrounding the restraint is included in the model as shown in Figure 11. The FE analysis showed that the maximum stress on the mirror can be as high as 3.9 MPa which is within the limit with a safety factor of 9 to the ultimate stress and a factor 3 to the allowable stress of Zerodur according to the standards applied to a GMT instrument, the GMT-Consortium Large Earth Finder (G-CLEF)^{[13][14]}.

Figure 11: Section view (left) and FE model (right) of a seismic restraint.

3.3 Mirror Cell Design

The main functionality of the mirror cell is to protect the mirror and to provide appropriate stiffness against static loads and dynamic operations. The mirror cell design, a weldment arrangement with thin walled aluminum plates made of heat treated AL 6061-T6 (see Figure 12), provides high stiffness and compactness. Stiffeners and reinforced mounting design at the support locations provide a strong structural integrity for direct load path.

The mirror cell also serves two functional purposes: 1) provide an interface between the FSM mirror and the M2 Positioner of the telescope by a kinematic mounting mechanism and 2) provide a sealed volume behind the mirror to balance the mirror gravity with a vacuum pressure. The mirror cell is pressurized to balance the mirror gravity during telescope operation. The gravity force parallel to the lateral support is balanced by differential pressure force on the mirror. Each of the three piezo actuators is mounted to the mirror cell through a load cell, which provides feedback reading of force to adjust the vacuum pressure. The balanced mirror gravity with the pressure at a zero load cell reading keeps the mirror in a floating state, where the gravity print-through effect on the optical surface becomes minimum. During the dPDR study, the vacuum control units such as valves and controllers have been evaluated and selected. Vacuum valve of LS-15V from Enfield Technologies is used as a proportional pneumatic valve for pressure control. For a pneumatic sensor, one of PFT series from SICK has been selected to measure the pressure. Trade studies to determine the preferred location for the edge seal have been performed for two different cases; 1) edge seal located at the back of the mirror and 2) located at the front flange. This difference causes a different distribution of force on the mirror and a corresponding difference in the optical performance; EE80 of 0.010 arcsec for Case 1 and 0.030 for Case 2. Also considering the accommodation of the metrology fiducials and edge sensors on the mirror, we selected Case 1 with edge seal located at the back of the mirror as shown in Figure 13.

Figure 12: Assembled view (left) and exploded view (right) of the FSM segment cell (the windscreen is not included).

Figure 13: Vacuum seal location between the mirror and the mirror cell (left) and windscreen in two parts over the sealing (right).

Figure 14: Integrated FE model of the FSM assembly with fixed boundary conditions at the M2 positioner interface (left) and the 1st natural mode at 75 Hz which is a torsional mode: rotation around lateral flexure (right).

An integrated model has been created including the mirror, the mirror cell, and key sub-assemblies for evaluation of the system performance. The main purpose of integrated modeling is to simulate scenarios in which the interaction between various components may be difficult to predict otherwise. Our analysis for the dPDR study has been focused on stresses at the glass interface during seismic events and mirror surface deformation during regular operation with and without active tip-tilt actuation. Integrated models are generally made at lower fidelity, but the modeling of FSM was done at high resolution at the mirror interfaces to obtain accurate stress results. For the seismic condition mentioned above, the maximum principle stress in the glass is 6 MPa at the location of the lateral flexure in the lateral acceleration case which corresponds to a safety factor of 6 to the ultimate stress and a factor 2 to the allowable stress. The stress values in the components other than the mirror are at least a factor of 5 below their yield stress limits. A modal frequency response simulation has been also performed to predict the mirror displacement and deformation during tip/tilt operation. In general the results of deformation are proportional to the tip-tilt amplitude and to the square of the frequency and are consistent with those from the mirror only model discussed in Section 3.1.

3.4 Control System Design

Design of the control system has been revised from the previous PDR design^{[7][9]} in each functionality as summarized in Table 3. For the tip-tilt control, we have changed the controller for piezoelectric actuators to provide enhanced power for high frequency control and a simpler and more efficient control architecture. Control interface has also been changed to a direct EtherCAT connection by the new controller. Vacuum control scheme has been revised to overcome the limitations of the old design concept found during the FSMP tests such as a periodic variation in residual pressure and concerns of stability and maintainability. We developed a new Matlab model for the tip/tilt control and the vacuum support control for model-based design and simulation^[15]. For the EtherCAT interface design, we have improved the early concept for an EtherCAT-based control system in the PDR design by selecting new EtherCAT terminals and making lists for data objects for the interface. We have also built a test system to test the communication and functionality of the EtherCAT interface. In addition, a temperature monitoring subsystem and a control system for the FSM AIT have been newly designed. All the details on the control system design are described in our separate paper by Jeong et al. (2018)^[11].

To evaluate the old design of the control system and identify required points of improvement, we have tested tip-tilt performance of FSMP more extensively in a more reliable testing environment including an enhanced mounting frame (see Figure 15). The tests were performed at four different inclination angles (0°, 30°, 60° and 90°) and basically with two frequencies of sinusoidal input (10 Hz and 20 Hz). Analysis on the test results showed that the design concept worked properly in general and also led us to find some problems in the PDR design such as non-linearity of the PZT actuator, noise in the controller and phase unbalance among the actuators, which can be solved by the design improvements described above. More details on the FSMP dynamic test are presented by Kim et al. (2018)^[16].

Table 3: Key changes and updates in the FSM control system design

Category	Component	PDR Design	Delta-PDR Design
Tip/Tilt Control	Controller	PI E-709.SRG single axis controller (3ea per segment)	PI E-727.3SDA three axes controller (1ea per segment)
	Controller Interface	SPI (SPI to EtherCAT)	EtherCAT direct connection
	Model	N/A	Matlab/Simulink model-based design
Vacuum Control	Flow Control	On/off valve	Proportional valve
	Pressure Sensor	N/A (FSMP: external gauge connected by hose)	Attachment type sensor (on the mirror cell)
	Model	N/A	Matlab/Simulink/Simscape model-based design
EtherCAT Interface	Hardware	Preliminary list of the EtherCAT terminals	Some EtherCAT terminals have been changed. Test system has been designed & constructed.
	Software	N/A	Lists of data objects
Temperature Monitoring		N/A	Newly designed
Control Test System for FSM AIT		N/A	Newly designed

Figure 15: Tip/tilt control test using FSMP at 60° inclination (left) and 90° inclination (right).

4. AIT PLAN

A fabrication, assembly, and integration plan for FSM has been developed including preliminary designs of associated equipment or jigs. Major parts or subcomponents of FSM have been identified and categorized as commercial parts or manufactured parts, and for each of the parts an inspection method has been defined. A preliminary procedure of assembly and integration for an FSM segment has been developed in 9 steps as summarized in Table 4. Test equipment needed for system integrated tests has been identified or designed conceptually, including a test tower and a testbed frame for the tests at different orientation angles between 0 to 90 degrees as shown in Figure 16. Details of the AIT plan are presented by Han et al. (2018)^[17].

Table 4: Assembly and integration procedure for an FSM segment

Step 1		Take mirror out of the shipping box using the mirror handling jig.
Step 2		Mount the mirror onto the assembly platform.
Step 3		Assemble the breakaway systems of axial supports under the mirror.
Step 4		Flip the mirror to facing down.
Step 5		Assemble the lateral support subassembly, seismic restraints, axial support sub-assemblies, and the tangential support.
Step 6		Mount the mirror cell onto the cell plate of the assembly platform.
Step 7		Integrate the mirror and the cell with fine adjustment for alignment. Assemble the spherolinder mounting adapters on the mirror cell.
Step 8-A		Remove the mirror handling jig and assemble the vacuum parts.

Step 8-B	<p>3M electrical tape 1/2" wide 0.020" thick, 50 ft minimum length (used to attach the vacuum seal) PVC strips 1/2" wide, 0.020" thick, 15 ft long (used to build a vacuum seal)</p> <p>Commercial PVC and 3M tape are considered for sealing referred from JCT heritage</p> <p>Section view of vacuum seal</p>	Attach the vacuum seal.
Step 8-C	<p>Top view of call and wind shield</p>	Assemble the wind shield.
Step 8-D	<p>Mask and aperture mask are assembled to measure the beam</p>	Assemble the aperture mask.
Step 9		Ready to be installed to the testbed frame or the M2 Positioner.

Figure 16: Schematic configurations for FSM system integrated tests at three different inclination angles of 0° (left), 45° (middle) and 90° (right).

5. CONCLUSIONS

The previous design of FSM from the telescope PDR has been revised through the dPDR study incorporating the lessons learned during the FSMP development and suggestions from the Phase 0 study for planning the project. New sets of requirements and ICDs have been provided and lower-level specifications and error budget have been derived for modeling and engineering for the design. Detailed analysis and performance evaluations including an integrated modeling have been conducted to improve the PDR design particularly for the lateral flexure, the breakaway system of the axial supports, the seismic restraint system, the tangent support, the vacuum support system and sealing, and interfaces with edge sensors and metrology fiducials. The control system has also been revised from the PDR design for tip-tilt control, vacuum pressure control, and control interface, assisted by model-based design and revised tip-tilt tests

for FSMP. Along with the design of FSM itself, a plan for AIT has been developed including preliminary designs of associated equipment or jigs.

ACKNOWLEDGMENTS

The design of FSM has been accomplished by dedicated and collaborative efforts of all the participating members at Korea Astronomy and Space Science Institute (KASI), National Optical Astronomy Observatory (NOAO), Korea Research Institute of Standards and Science (KRISS), Institute of Advanced Engineering (IAE), and the GMT Organization (GMTO).

REFERENCES

- [1] Cho, M. K. et al., "Design and development of a fast-steering secondary mirror for the Giant Magellan Telescope," Proc. SPIE 8125, 812505 (2011)
- [2] Cho, M. K. et al., "Development of GMT fast steering secondary mirror assembly," Proc. SPIE 9145, 91451M (2014)
- [3] Cho, M. K. et al., "Development of a fast steering secondary mirror prototype for the Giant Magellan Telescope," Proc. SPIE 8444, 844420 (2012)
- [4] Kim, Y. -S. et al., "Development status of the prototype of the GMT fast steering mirror," Proc. SPIE 8415, 84150B (2012)
- [5] Corredor, A. et al., "Optomechanical analysis and testing of a fast steering secondary mirror prototype for the Giant Magellan Telescope," Proc. SPIE 8836, 88360U (2013)
- [6] Kim, J. et al., "Development of a FSMP mirror assembly," Proc. SPIE 9582, 95820K (2015)
- [7] GMTO Corp., "GMT System Level Preliminary Design Review," GMT-SE-RVW-00410 (2014)
- [8] Lee, S. et al., "Development of the Fast Steering Secondary Mirror Assembly of GMT," Proc. SPIE 9912, 991241 (2016)
- [9] GMTO Corp., "GMT Preliminary Design Report for Telescope Subsystem," GMT-TEL-RVW-0045 (2013)
- [10] Cho, M. K. et al., "Design of the fast steering secondary mirror assembly for the Giant Magellan telescope," Proc. SPIE, 10706, 10700-5 (2018)
- [11] Jeong, U. et al., "Design and prototype test of control systems for the fast-steering secondary mirror of GMT," Proc. SPIE, 10700, 10700-146 (2018)
- [12] Kim, Y. et al., "Experimental study of breakaway system for the fast-steering secondary mirror of GMT," Proc. SPIE, 10706, 10706-163 (2018)
- [13] Szentgyorgyi, A. et al., "The GMT-Consortium Large Earth Finder (G-CLEF): An optical echelle spectrograph for the Giant Magellan Telescope (GMT)," Proc. SPIE, 10702, 10702-63 (2018)
- [14] Oh, J. et al., "Detailed design of the G-CLEF flexure control camera subsystem," Proc. SPIE, 10702, 10702-326 (2018)
- [15] Dribusch, C. et al., "Tip/tilt and pressure control modeling of the fast steering secondary mirror for GMT," Proc. SPIE, 10705, 10705-37 (2018)
- [16] Kim, S. et al., "Tip/tilt performance test of FSMP for development of the GMT FSM," Proc. SPIE, 10700, 10700-134 (2018)
- [17] Han, J. -Y. et al., "Preliminary AIT plan for the FSM segments of GMT," Proc. SPIE, 10700, 10700-82 (2018)