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The Giant Magellan Telescope Enclosure

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ABSTRACT

The Giant Magellan Telescope (GMT), one of three next-generation extremely large telescopes (ELTs), will have a 25.4-meter diameter effective aperture, composed of seven 8.4m primary mirror segments, and will be located on the summit of Cerro Las Campanas (~2500m elevation) in Atacama Desert region of Chile. Developing a new observatory for cutting-edge science operations and a 50-year lifespan poses a variety of complex structural, mechanism, and control systems design challenges. This paper presents the final design of the GMT enclosure, which is composed of a cylindrical rotating heavy movable structure supported by a fixed structure of conventional construction. The lower enclosure is ~12m (40 ft) tall and carries the upper enclosure which rotates freely and opens to allow the telescope to view the sky. The rotating upper portion is ~52m (173 ft) tall, with a total rotating mass of ~4800 metric tonnes (MT, ~10.5 million lbs.). The rotating upper enclosure carries a pair of bi-parting shutter doors, which are closed during the day to protect the telescope, and open during the night to provide the telescope with an unobscured view of the night sky. The upper Enclosure Rotation System (ERS) carries the movable structure on an electrically driven set of trollies (bogies) which ride on a double-rail track system. The "L" shaped shutter doors are heavy movable structures themselves, with a vertical span of ~47m (155 ft), a horizontal span of ~50m (165 ft), and a combined mass of 667 MT (1.47 million lbs.). To modulate the wind environment around the telescope at night, the enclosure also provides a deployable wind screen (~27m wide, ~30m tall, 164 MT (360,000 lbs.)), and over 300 wind vents (using commercial roll-up doors).

In late 2021, the non-profit GMT corporation (GMTO) selected IDOM (Bilbao, Spain) to develop the enclosure from a preliminary reference design through to final design and construction documents (drawings and specification). Over the last 2.5 years, the designs for enclosure structures, mechanisms, telescope pier seismic isolation system, telescope utilities, and related control and safety systems have been refined as they passed through a 60% critical design review (CDR) in 2023 and a final design review (FDR) in 2024. This paper provides a brief description of the enclosure functional and performance requirements, and then discusses the tools and design approaches for the enclosure, including the use of Building Information Modeling (BIM), application of dynamic 3D models for visualization of interactions between the telescope and enclosure, computational fluid dynamics modeling of the site and enclosure, and the incorporation of a Building Automation System (BAS) for management of access control, security, audio/video monitoring, lighting, HVAC, and related building functions.
Keywords: GMT, observatory, facilities, enclosure, construction

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Introduction

FIGURE 1: GMT ENCLOSURE

The Giant Magellan Telescope (GMT) is a 25.4-meter, optical and mid-infrared (320–25000 nm), ground based, extremely large telescope under construction on the grounds of the Las Campanas Observatory in Chile's Atacama Desert. Once complete, it will be the largest Gregorian telescope ever built, with a resolving power 10 times that of the Hubble Space Telescope and four times that of the James Webb Space Telescope.

GMT Site

The GMT telescope will be located on the peak of Cerro Las Campanas, one of the highest seismicity areas worldwide, at an altitude of 2,515 meters above sea level, in the Coquimbo region of Chile, approximately 160 km northeast of the city of La Serena. The GMT site is within the Las Campanas Observatory (LCO) boundaries and the site master plan is distributed across three main areas: the

Summit, Support Site 1 (SS1), and Support Site 2 (SS2), housing the systems and facilities for the operation of the observatory.

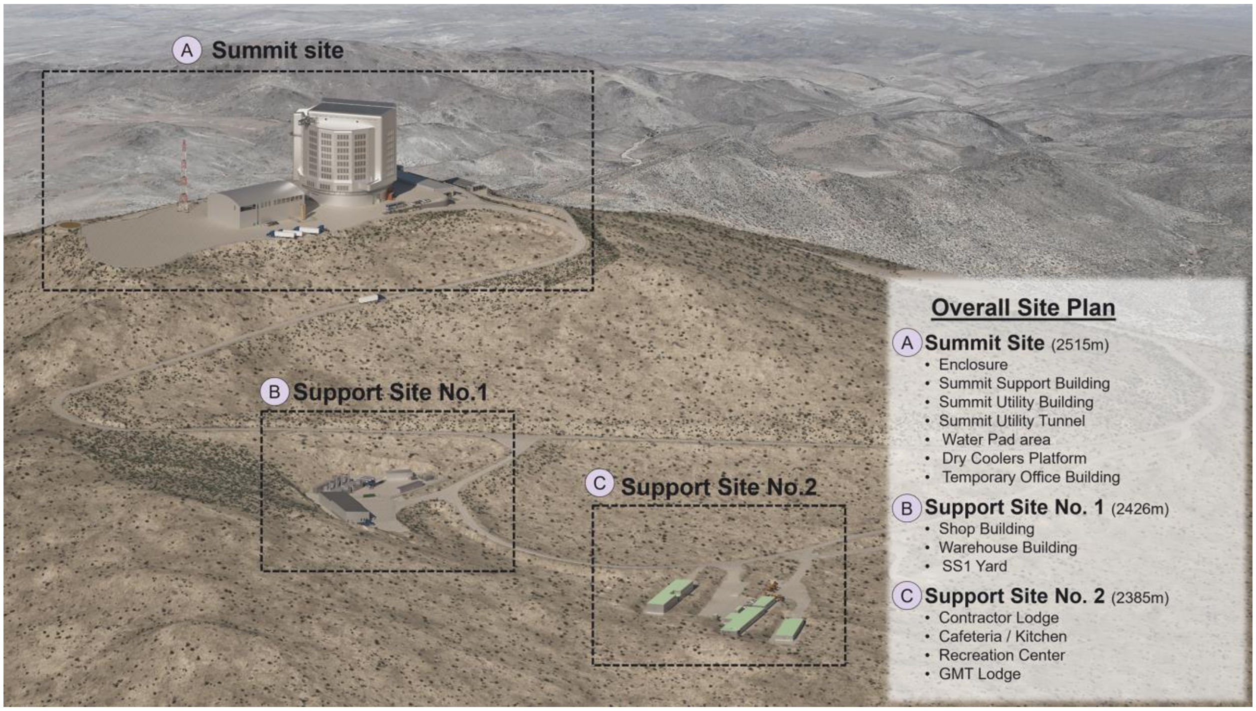

FIGURE 2: GMT SUMMIT SITE

At the Summit, in addition to the Telescope and the Enclosure, the main facilities necessary to support nighttime science operations and essential daytime operations or maintenance support are also located, housed in the Summit Utility Building (SUB) and Summit Support Building (SSB) respectively.

Support Site No. 1 mainly houses the infrastructure to receive and distribute the incoming electrical power and fiber trunk lines to the summit and other facilities at SS1 and SS2.

Other facilities needed for non-critical maintenance functions and non-essential daily activities are housed at either additional area in Support Site No.1 (Shop Building, and Warehouse Building) or Support Site No. 2. (Residence site, houses staff and visitors).

Enclosure Overview

The enclosure is a 65-meter-tall movable structure responsible for sheltering the GMT telescope’s mirrors and components from adverse site conditions, such as severe earthquakes, heavy winds, or extreme temperatures. It is also responsible for enabling the daily science operations and maintenance activities to be carried out at the observatory.

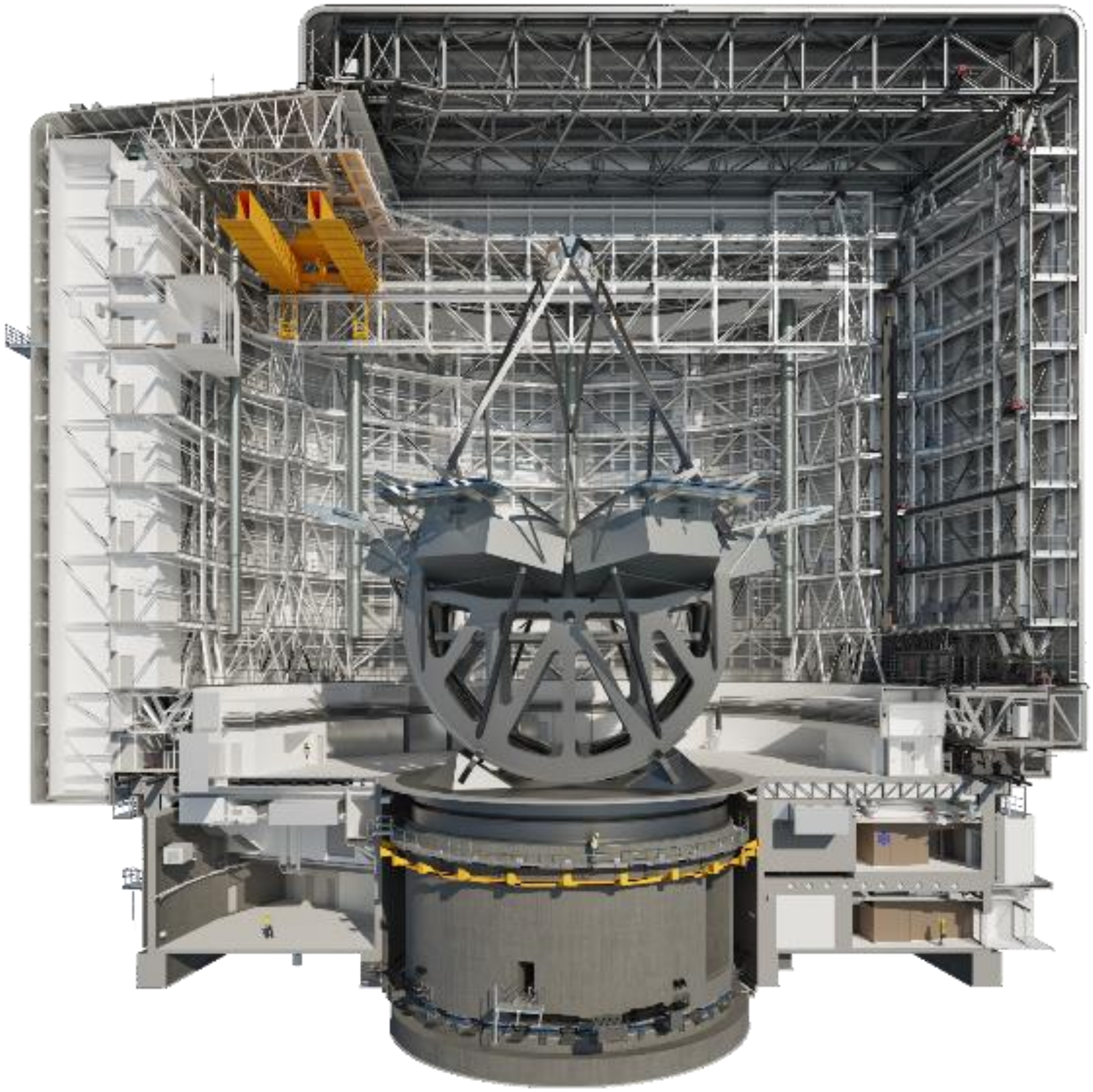

FIGURE 3: ENCLOSURE SECTION

The upper, rotating portion of the Enclosure structure is called the Upper Enclosure. It is approximately 52m tall with a mass of 5500 metric tons. The Upper Enclosure contains the rotating structure and attached mechanisms which enable nighttime science observations.

The Upper Enclosure carries the Bi-Parting Shutters, Enclosure Overhead Bridge Crane, Wind Vents, Wind Screen, and other equipment vital to observatory operations. The drive and support system for the Upper Enclosure is called the Enclosure Rotation System (ERS). This system consists of both driven and idler bogies attached to the moving Upper Enclosure that ride on rails installed on the static Lower

Enclosure. The ERS double-rail system has inner and outer radii of 27.675m and 29.525m meters respectively.

The lower portion of the Enclosure structure is called the Lower Enclosure and rises ~12m above the summit grade level. Its main structural components are the concrete inner and outer ring walls, the telescope pier, and the observing floor. In the Lower Enclosure reside the Observatory Control room, the IT room, and the Computer Room, all of which are required for normal observatory operations. Also, the Lower Enclosure contains the science instrument Labs, Utility room, Open Storage area, Shipping and Receiving area, canteen, shared workspace, and a kitchenette.

The upper enclosure can complete a full rotation in four minutes supported on 33 fully compliant bogies which rotate the structure to co-align with the telescope. The 46 meter tall Bi-Parting Shutter Doors are supported on eight compliant bogies and open to allow the telescope to view the night sky. The upper enclosure opens to the sky with two 46-meter-tall shutter doors, weighing ~500 metric tons each, supported on (4) lower and (4) upper compliant bogies, which provide the 25.4-meter telescope with an unobstructed view of the sky for nighttime scientific observations.

Operational Concepts and Functional Requirements

The Enclosure fulfills the following primary and key functions:

- Provides environmental protection for subsystems inside the enclosure, including protection from precipitation, wind, dust, stray light, and seismic events (shutter, wind screen, wind vents, telescope pier seismic isolation system)
- Provides environmental control inside the enclosure during observations (wind vents, windscreen and forced ventilation) and during daytime (air conditioning)
- Provides material handling infrastructure for moving large subsystems from one part of the Enclosure to another, or to grade, including primary mirrorM1 cells, the Mount Top End, and instruments (bridge crane, pier lift platform, access hatches).
- Provides personnel work areas for instrument assembly, integration, test, and maintenance (low and high-bay lab areas in lower enclosure)
- Provides spaces for observatory control low-latency system computer systems and network equipment (server room and information technology (IT)IT room)
- Provides personnel work areas for day and nighttime operations (control room, meeting room, kitchen, office space, bathrooms, labs, loading dock)
- Provides personnel and equipment access to all service points on the telescope and enclosure (elevators, catwalks, stairways, lifts, etc.)
- Provides safety functions, features, and systems to enable safe operations and maintenance of the telescope, instruments, and enclosure subsystems (access control, audio and video communications, and environmental monitoring).
- Provides the Telescope Pier whose role is to support the telescope and its payloads.

At night, the GMT Enclosure protects the telescope from adverse environmental conditions while providing an unobstructed opening for the telescope field of view. During the day, in addition to protecting the telescope from the environment, the GMT Enclosure supports O&M (Operations and Maintenance) activities. The Enclosure supports these activities by providing controlled environmental conditions, utilities, access platforms, and handling equipment.

The enclosure also provides the telescope pier and a seismic isolation system that can survive the strongest earthquakes expected over the 50-year lifetime of the observatory and will allow the telescope to quickly return to operations after the more frequent, but less intense seismic events that are experienced several times per month.

One of the most important and frequently performed O&M activities at the observatory will be the periodic removal of sections of the telescope mirror for maintenance and recoating. This process involves using the Enclosure Overhead Bridge Crane, a 2-axis bridge crane installed in the moving Upper Enclosure.

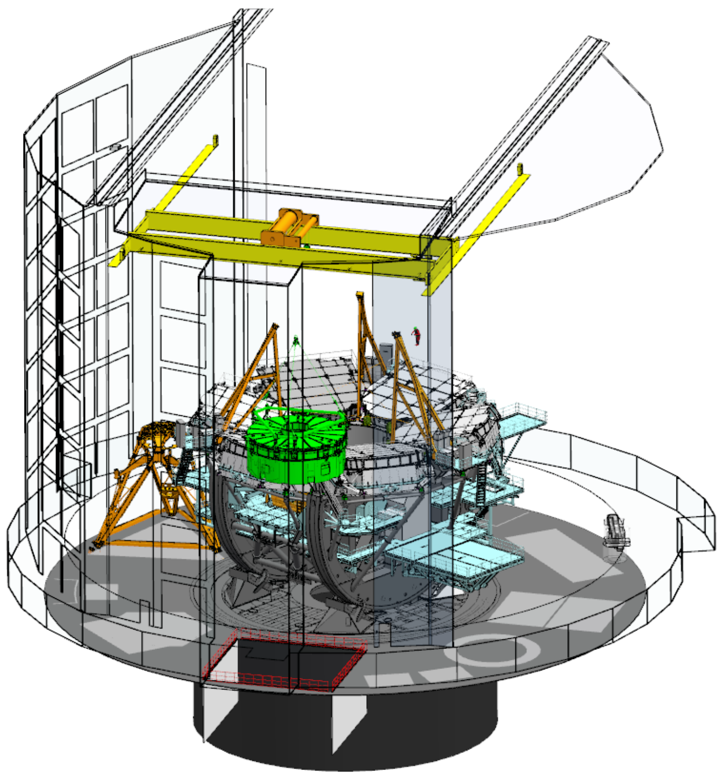

FIGURE 4: MIRROR CELL EXCHANGE

In general, the Enclosure will facilitate access to the telescope using a combination of permanent access platforms and special equipment. This equipment includes forklifts, scissor lifts, permanently installed articulated boom lifts, cranes, and elevators.

Design Approach

Safety is a major design driver for the Enclosure. Movable structures and mechanisms involve inherent risks that must be considered for reliable and safe operation. Due to the complexity and uniqueness of the GMT Enclosure, Safety has two sides:

- The Enclosure as a building, complying with the standards associated with the structural design, MEP design, Fire design and emergency evacuation, noise and occupational health and safety guidelines

- The Enclosure as a machine, following the safety machinery standards.

During the detailed engineering process, a complete hazard analysis was developed following MIL-STD-882E. Hazardous areas have been defined and potential risks identified and evaluated, determining severity and probability, and recommending mitigations. These mitigation measures have been incorporated in the design to minimize the residual risks.

The enclosure was designed with a focus on availability. Critical systems required for nighttime science operations and daytime operations incorporate redundancies that allow the observatory to continue operations in the event of a failure. Examples of redundant systems are the electrical supply, Dynamic/Rotary UPS (DRUPS), cooling systems, Enclosure Rotation System bogies and Bi-Parting Shutter bogies.

Accessibility to all components of the Enclosure has been guaranteed for assembly and maintenance operations. The layouts have been adjusted to the final design solutions to provide sufficient space for installation and removal of components and special maintenance equipment has been designed when conventional tooling was not sufficient for the operations.

A Failure Mode and Effect Criticality Analysis (FMECA) has been performed for all Enclosure systems, identifying potential failure modes for each system, and analyzing whether any additional mitigation measures are needed.

A Reliability, Availability and Maintainability (RAM) study has been developed to assess the performance of the system in meeting the required operational objectives. In particular, the availability of the Point To Point Grid Connection System, Enclosure Utilities, Power Distribution, Enclosure HVAC, Enclosure Active Ventilation System, Facilities ISS and facilities Controllers, Enclosure Rotation System (ERS), Pi-Parting Shutters, and Windscreen have been addressed to confirm that the design fulfills with the specific requirements and with the Enclosure general availability requirements.

Building Information Modeling (BIM) Integration

The GMT Enclosure design required collaboration between many engineering specialties including structural, mechanical/electrical/plumbing (MEP), building automation, civil works and architecture. BIM tools have been used to ensure seamless integration and coordination between the design teams. BIM has also been used to communicate between project stakeholders and to evaluate construction costs and plan the construction process.

An integrated model of the Enclosure was created in Navisworks. This model takes information from several software platforms to create a combined multidisciplinary representation of the Enclosure. Some of the software platforms used in the design include:

- Tekla for steel structures
- Revit for concrete, architecture, and MEP installations
- SolidWorks for mechanisms and control
- Instram for civil works.

The BIM level of detail (LOD) varies depending on the needs of each discipline ranging between a minimum of LOD300 up to LOD400 for the mechanisms.

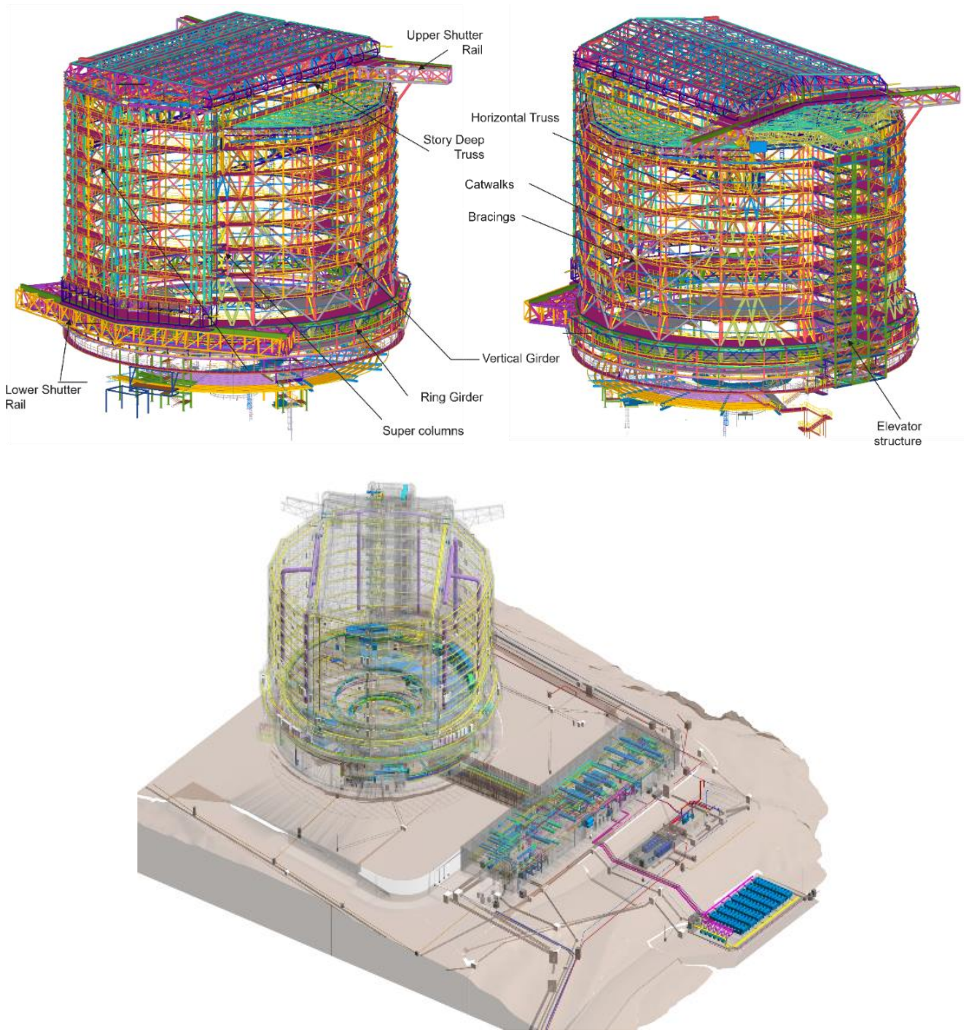

FIGURE 5: BIM INTEGRATION OF STRUCTURES, MECHANISMS, MEP AND CONTROLS

Dynamic Simulation Tool

The GMT is the next generation of land-based observatories and is much larger than its predecessors. With the increase in size comes increased difficulty and complexity associated with executing daily operations tasks. Simulation of these tasks, especially during the design process, can function as an advanced means of assessing risk and assisting in design mitigation. Game development engines offer an efficient avenue for simulation of a wide variety of operations behaviors. Using a game development engine, like Unreal Engine, a virtual observatory can be created with motion and basic physics. With Unreal, a distributable platform can be made that people with less computer literacy can use. Models created during the design process on BIM platforms like Revit, SolidWorks and Navisworks can be imported directly into Unreal which greatly speeds the production of the dynamic model.

FIGURE 6: DYNAMIC SIMULATION ENVIRONMENT IN UNREAL ENGINE

Use Case and Operations Simulation

Operations of the GMT will be complex and will involve handling of extremely heavy and extremely valuable scientific equipment. Extra care must be taken to develop use cases that are efficient and safe. Simulation of observatory operations use cases before they are attempted at the site offers an excellent way to reduce risk to the project. Game Engines are designed for this exact purpose. Simulation of complex physical environments where a user must achieve a set task.

Within the simulated observatory, behaviors can be carried out with basic physics and collision. Personell and handling equipment move in real time to accomplish a task allowing it to be refined and made more efficient. New hazards can be discovered during the process and new mitigations introduced to make processes safer. Multiple users can work together at the same time from multiple locations. For example, a crane operator can be positioned on the observing floor on one PC and a spotter on an upper catwalk at another with the two communicating via voice.

The working environment can also be simulated. Confined spaces can be identified, and appropriate procedures introduced. The number of people assigned to a task can also be tested. The speed of a task can also be determined and optimized. Allowing procedures to be improved before they are performed in the remote observatory environment.

Operations & Maintenance Training

FIGURE 7: SCISSOR LIFT IN DYNAMIC SIMULATION

Gamification of operations training can allow for extensive training off the mountain before personnel arrive on sight or handle science equipment. This offers an opportunity for increased safety by allowing personnel to familiarize themselves with procedures before they handle glass or other sensitive components.

BIM metadata can be imported along with geometry into game engines and used as a resource. For example, part numbers and manuals can be called up in real time for maintenance items.
Training can be conducted with simulations of actual real-world equipment. Control panels can mimic their real-world counterparts. Handling equipment motion can directly match the spec sheet.
The virtual observatory can also function as an orientation tool, allowing someone to explore the facility on their own and get a good understanding of the layout and safety features.

Major Mechanisms Design

The GMT Enclosure mechanisms are responsible for providing the Enclosure with the necessary movement capabilities to support nighttime science operations and essential daytime operations or maintenance. The Upper Enclosure contains several key mechanisms including: the Enclosure Rotation System (ERS), Bi-Parting Shutters (BPS), Windscreen (EWS), Wind Vents (EWV) and Enclosure Overhead Bridge Crane (EOBC). In this paper we will focus on the ERS, BPS and EWS as they are the most directly related to observatory science operations.

Enclosure Rotation System (ERS)

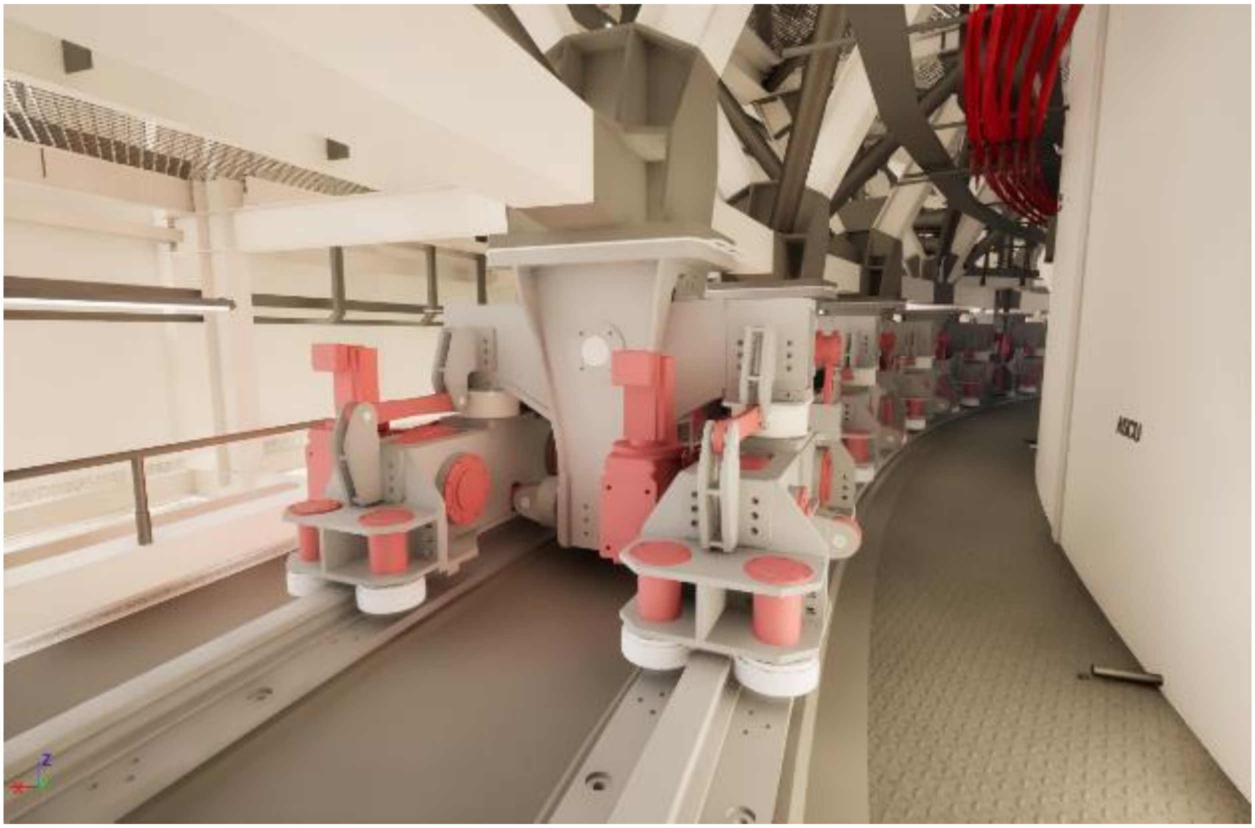

FIGURE 8: ENCLOSURE ROTATION SYSTEM IN BOGIE CORRIDOR

The ERS is responsible for the rotational positioning of the upper enclosure, allowing uninterrupted 360º rotation and an additional degree of freedom to the overhead bridge crane. The ERS consists of an arrangement of 33 pairs of driven bogies. Each pair is connected by an upper frame distributed in specific positions to optimize load distribution. The bogies ride on a double DIN A150 rail installed on the concrete ring wall of the fixed Lower Enclosure.

In order to protect the bogies against external conditions and control machinery heat output, the ERS is located in an enclosed space known as the bogie corridor. This area is designed considering maintenance access.

The 33 ERS bogies have been distributed in such a way to minimize the peak loading on any one bogie during operation. This results in a more uniform load distribution and load peak decrease. This optimization takes into account the shifting load of the Upper Enclosure due to the opening and closing of the Bi-Parting Shutters.

FIGURE 9: INDIVIDUAL BOGIE LOADING DURING OPERATION

Each bogie assembly consists of a pair of driven two wheel trucks (lower bogie) attached to an equalizer frame. Each lower bogie connects to the equalizer frame with a compliant elastomeric pad. This pad has two functions: to provide vertical compliance and encourage vertical load sharing between all of the bogie assemblies, and to provide a small amount of twist compliance to accommodate imperfections in the rail installation. Elastomeric pads have been selected to obtain the desired stiffness as they are a simple, compact and proven solution that has already been used in existing observatories. These components provide relevant advantages such as vibration isolation, dampening characteristics and low shear stiffness that enables each individual bogie to have a greater self-alignment capacity.

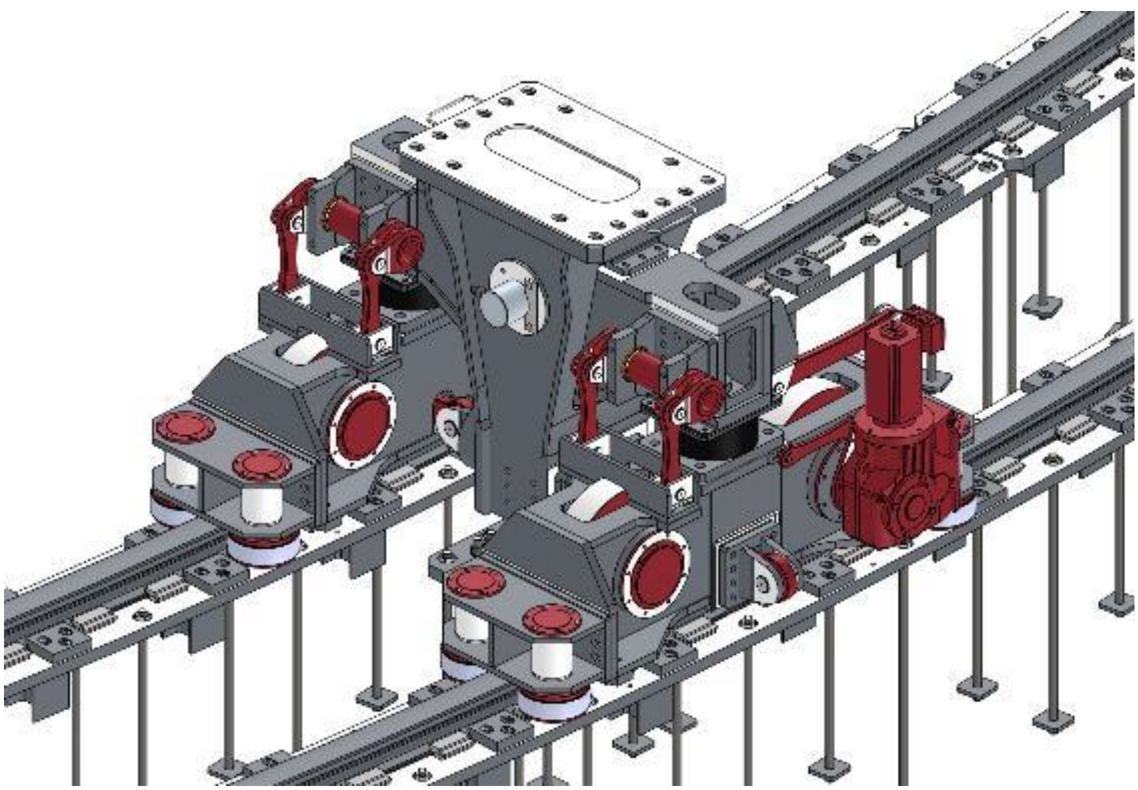

FIGURE 10: BOGIE ASSEMBLY

Loads coming from the Enclosure acting radially are taken by radial guide rollers that contact the sides of each rail. The lateral guide rollers also facilitate self-alignment of the bogies. These rollers are mounted on eccentric axles, allowing adjustment during assembly.

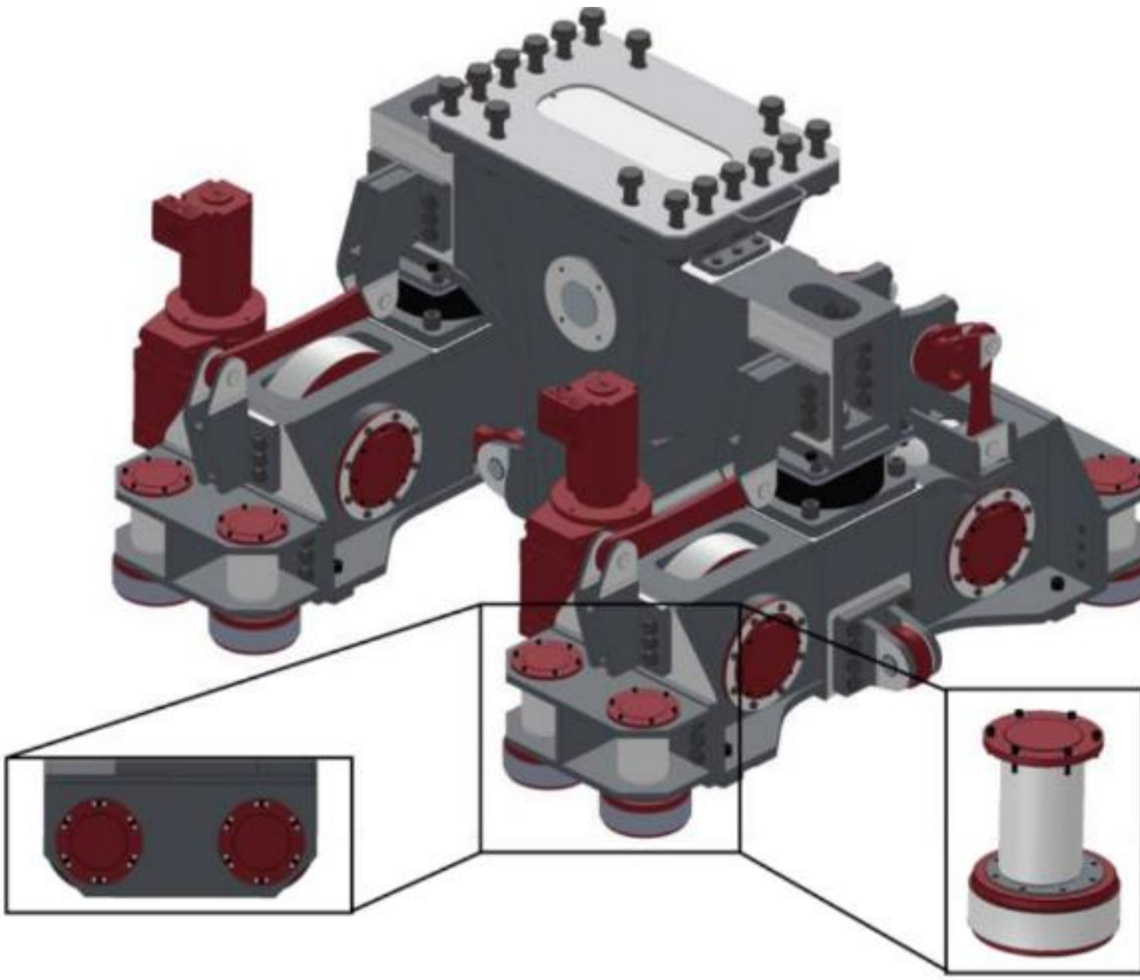

FIGURE 11: LATERAL GUIDE ROLLER

Radial loads are transmitted through the equalizer frame into compliant radial link arms. These link arms are made up of stacks of disc springs. The radial disc springs work in pairs, so they are only subjected to compression loads. Disc springs have been selected to obtain very low stiffness within the available space in order to absorb radial misalignments, improving the self-alignment of the bogies and encouraging load sharing between bogie locations.

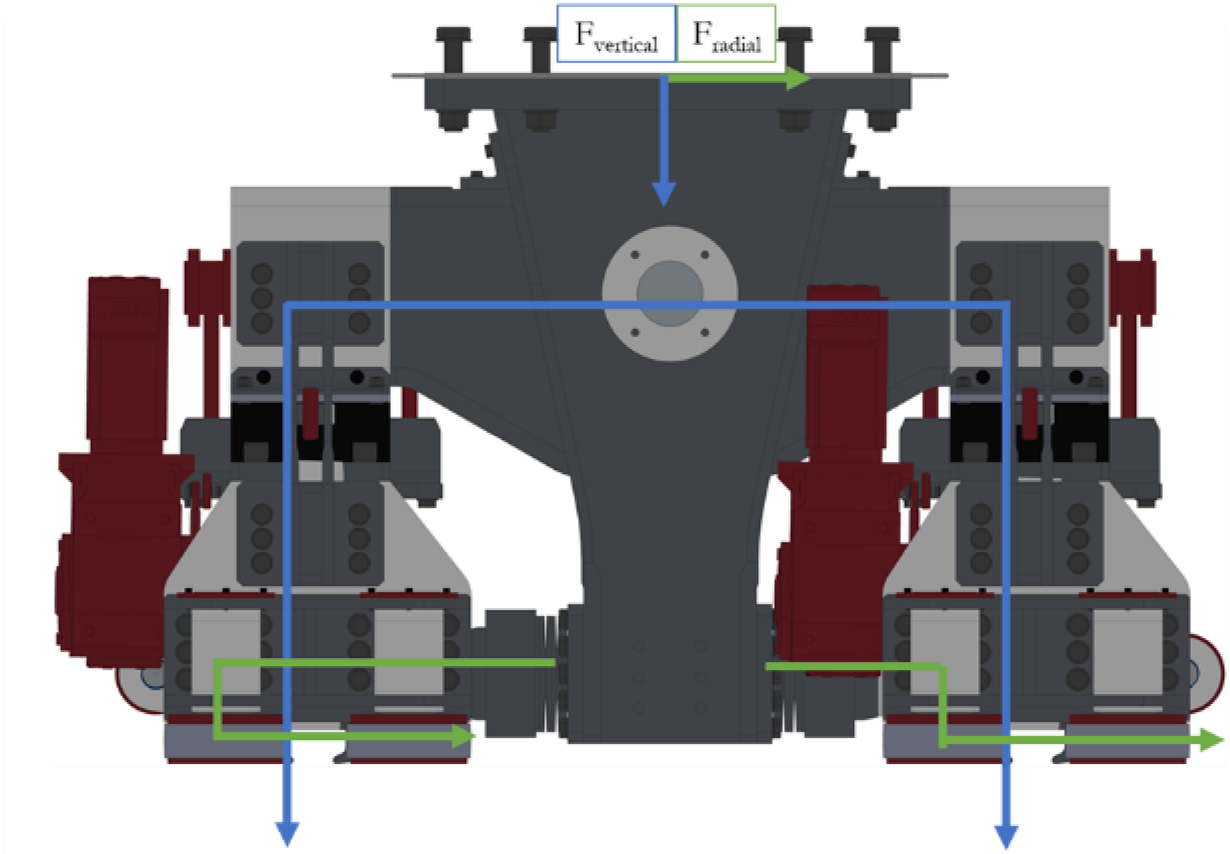

FIGURE 12: BOGIE VERTICAL AND RADIAL LOAD PATHS

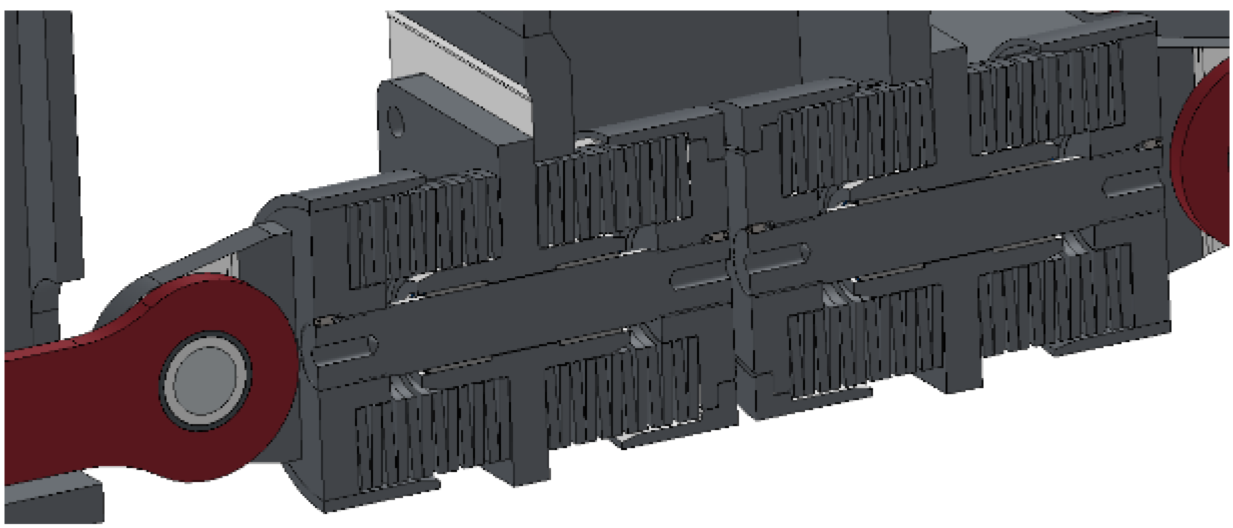

FIGURE 13: RADIAL LINK ARM WITH DISC SPRINGS

In order to avoid roll rotation, a high stiffness torsion rod is included in each bogie. Spherical plain bearings at both ends of the rods allow vertical and horizontal relative movement of the upper frame with respect to the lower frame.

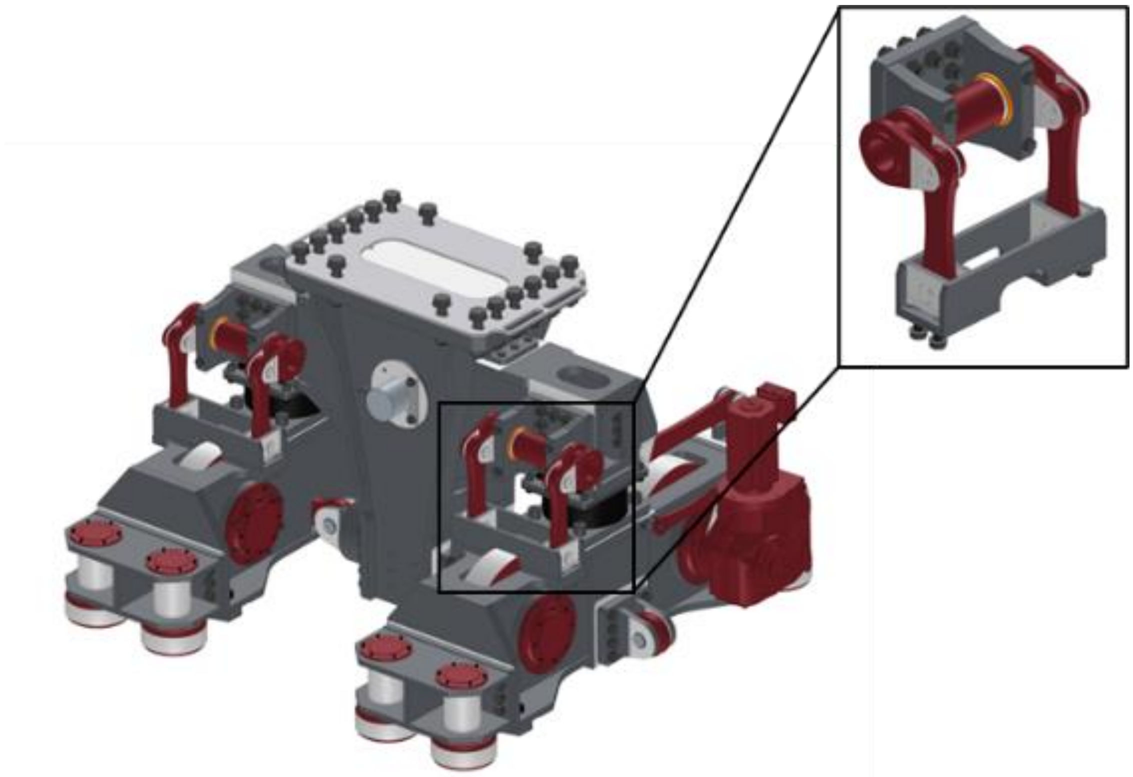

FIGURE 14: TORSION RODS

Driving force is transmitted to the Enclosure through a tangential link rod at each lower bogie. Either side of this rod is attached using a spherical roller bearing.

Due to the magnitude of extreme loads, vertical and radial hard stops are included in the bogie design. They create a separate load path for severe, non-operational, loads. Consequently, the elastomeric pads and disc springs can be defined for an optimal performance under operational loads while ensuring the integrity of the system under severe one-time loads. In addition, in case of component failure, these stops will prevent the bogies from losing their ability to take load.

Since the elastomeric pads are only meant to work under compression, uplift bar rods are included in the design to transmit vertical traction loads and also for maintenance purposes. These loads are transmitted to the rail via uplift clips.

A traction bogie system has been conceived for the ERS drive system, due to its advantages regarding the complexity of the system and the manufacturing and installation requirements. Each lower bogie has one gearmotor driven wheel. Considering the required traction capacity of the ERS system 33 pairs of bogies have been considered. Considering that the regular operation of the telescope will be at low speeds due to tracking activities, synchronous servomotors are considered in the design, targeting an enhanced efficiency and heat generation behavior at usual tracking speeds.

Conical shaped wheels with tilted shafts have been used. This ensures that the wheels will tend to move along a circular path with a defined center. This approach is good practice for achieving kinematic compliance and reducing wear on the mechanisms.

Bi-Parting Shutters (BPS)

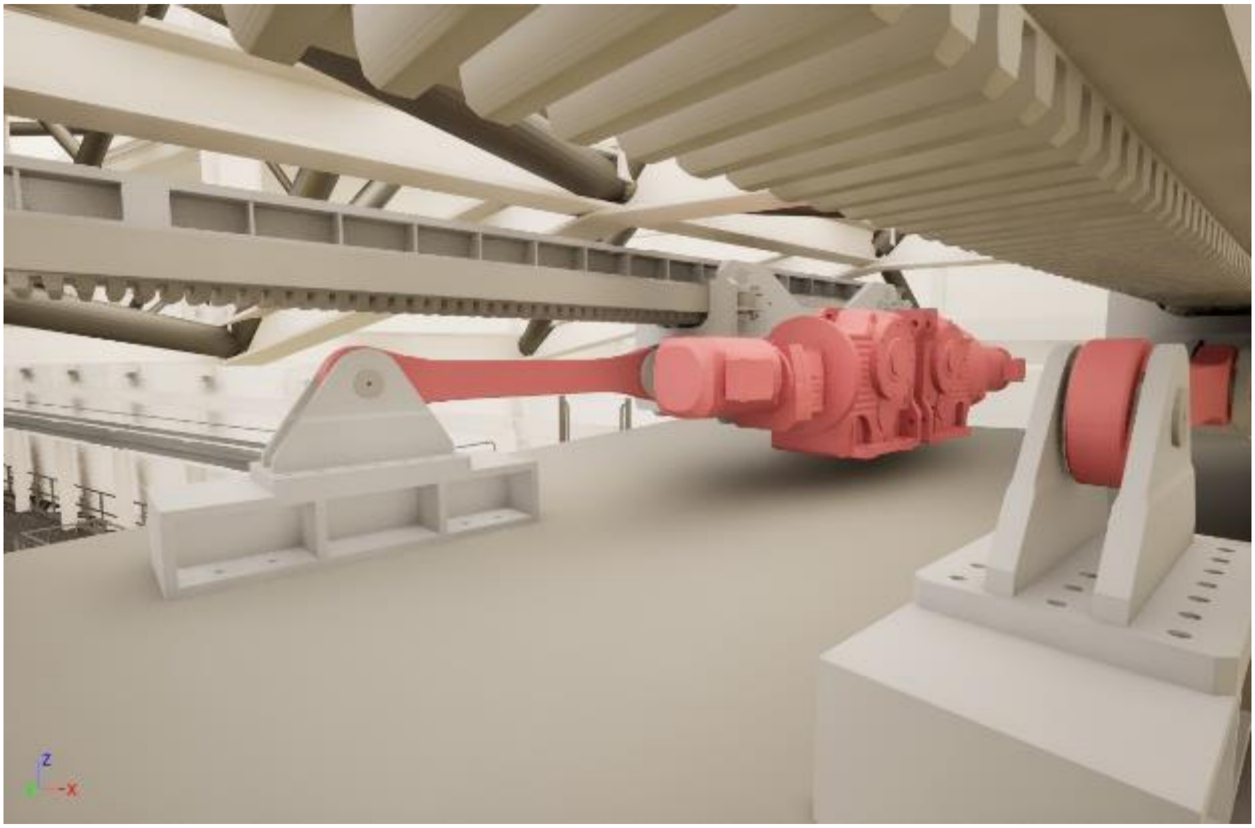

FIGURE 15: BI-PARTING SHUTTER DRIVE

The Bi-Parting Shutters (BPS) are the large, independently operated L-shape structures that protect the telescope from adverse external conditions and allow telescope observation when in the open position.

The BPS are driven using a rack and pinion system located on the extreme ends of each shutter. The racks are installed on the shutters themselves while the pinion gearmotor blocks are on the Upper Enclosure main structure. The system is duplicated at each driving position, and each shutter has in total four gearmotor blocks and four racks. This is to provide redundancy.

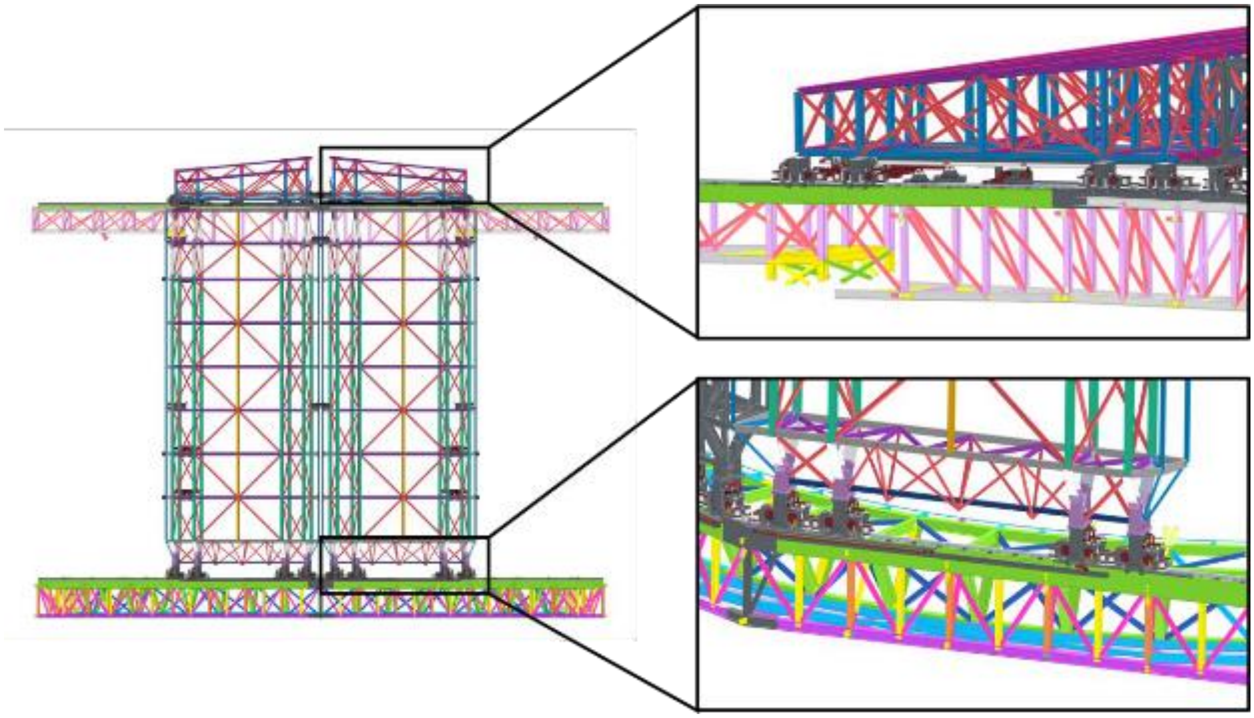

FIGURE 16: BI-PARTING SHUTTER LOCATIONS

The gearmotor block is a floating system, whose self-weight is supported on the shutter structure and is guided in 5-DOF by means of rollers, ensuring optimal contact between the rack and pinions. The gearmotor block is connected to the enclosure by means of a tangential rod, allowing only tangential loads to be transmitted. Two gear-motors are installed per gearmotor block to reduce the size of the required rack.

The shutters are held in place using motor brakes, a hydraulic caliper latch and a clamp latch mechanism. The hydraulic caliper latch counteracts the force created by the inflatable seals and ensures the integrity of the seals in areas far from the drive system. The clamp latch prevents large relative deformations in the closed position during extreme situations, such as survival winds or during crane operation.

The end of each rack is equipped with two pairs of polyurethane end of travel bumpers, which are designed to be able to stop the shutters from their maximum velocity in the case of overtravel.

The BPS (8) support bogies are located at the edges of the shutters panels. The bogies are attached to the shutter structure, coinciding with structural nodes for more efficient load sharing. The bogies ride on rails which are connected to the moving upper enclosure.

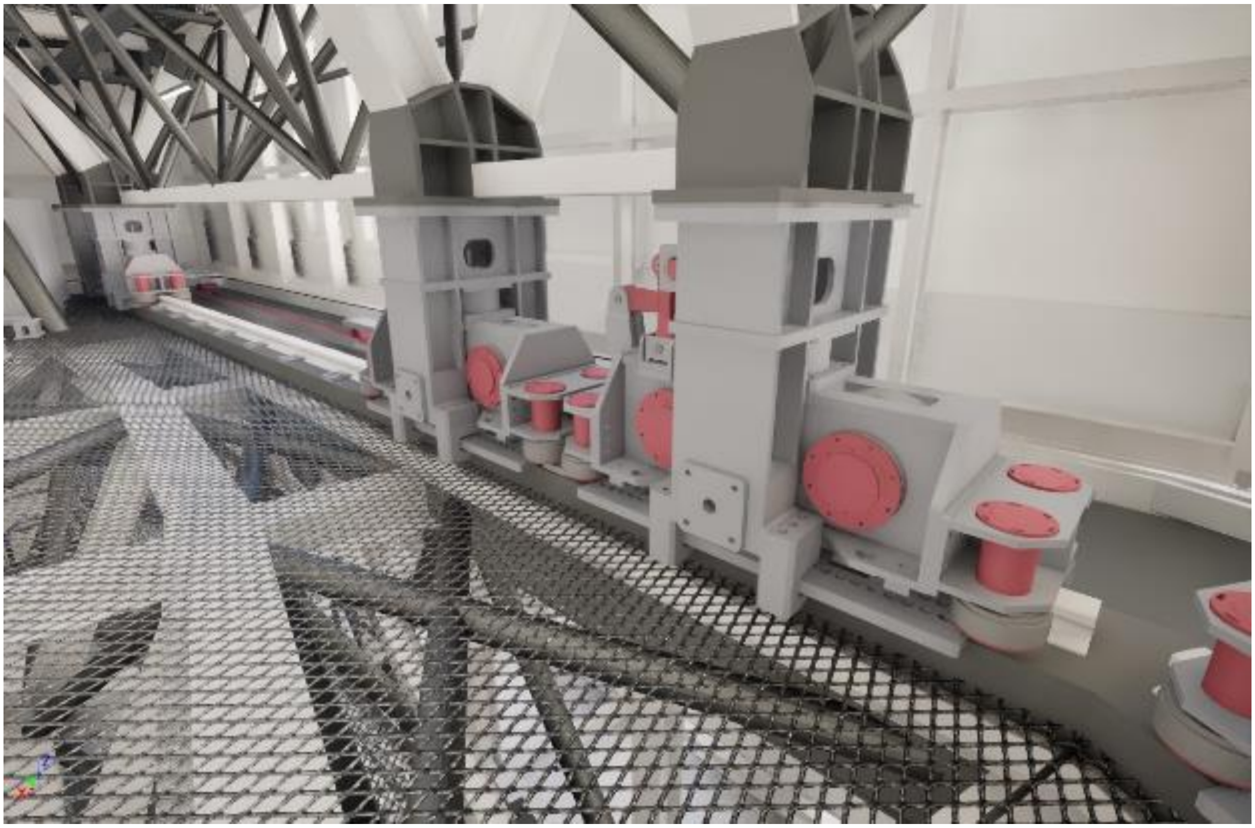

FIGURE 17: BPS SUPPORT BOGIES

Each support bogie is kinetically equivalent to the lower bogies of the ERS. They attach to the structure using a compliant connection and an elastomeric pad for load sharing between bogie assemblies. They have a similar torsion rod and tangential link arm design to the ERS bogies. They also have a similar lateral guide roller arrangement and uplift resistance design.

Enclosure Wind Screen (EWS)

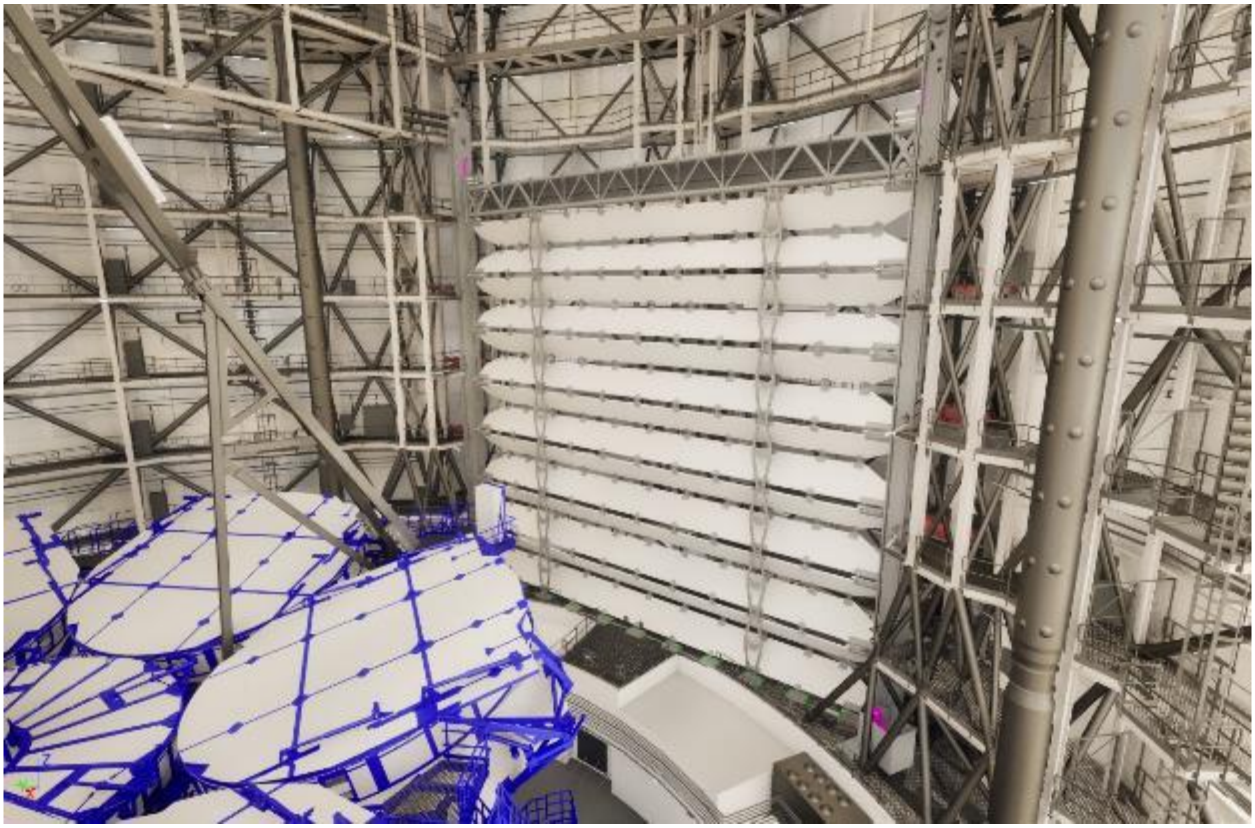

FIGURE 18: EWS IN THE DEPLOYED POSITION

The EWS mitigates wind loads on the telescope. It is a deployable barrier with a maximum dimension of roughly 25m by 25m. The function of the wind screen is to attenuate the flow of wind onto the telescope. The fully deployed EWS allows for the passage of wind on about 25% of its surface. A small amount of wind is desirable, but high wind speeds can cause the quality of the images to degrade. In operation, the wind screen follows the lower edge of the telescope's line of sight to provide the maximum possible wind protection.

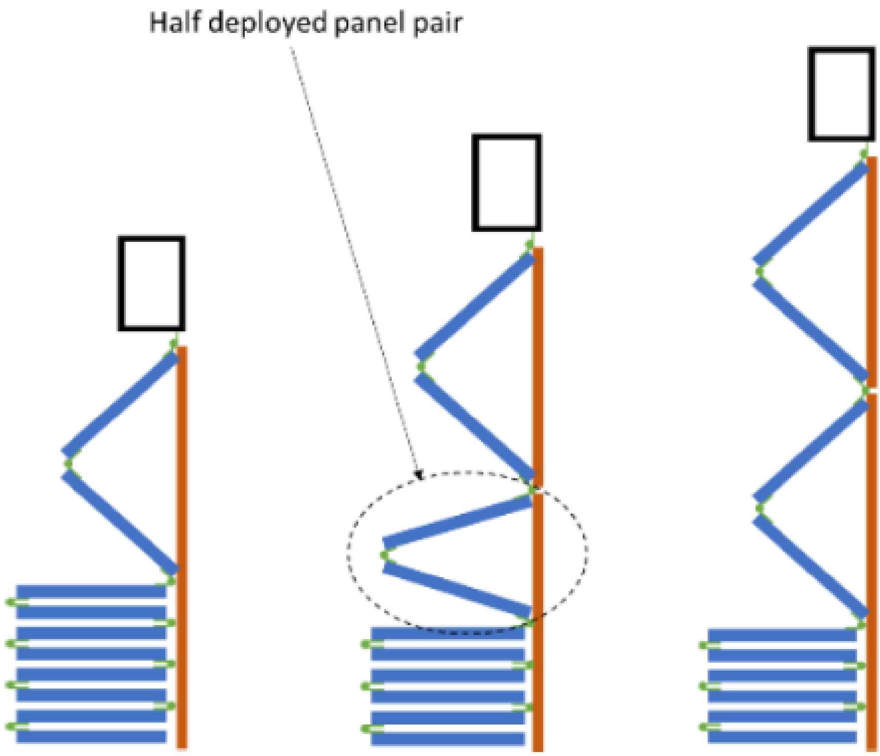

FIGURE 19: WIND SCREEN DEPLOYMENT

The EWS consists of composite panels similar to those used in wind turbines. The panels are based on a sandwich concept with a central foam core and two external GFRP skins. These panels are connected to each other using a hinge and tie rod system. The panels connect to a steel lattice lifting beam which is raised and lowered using a pair of chain hoists on either side of the screen.

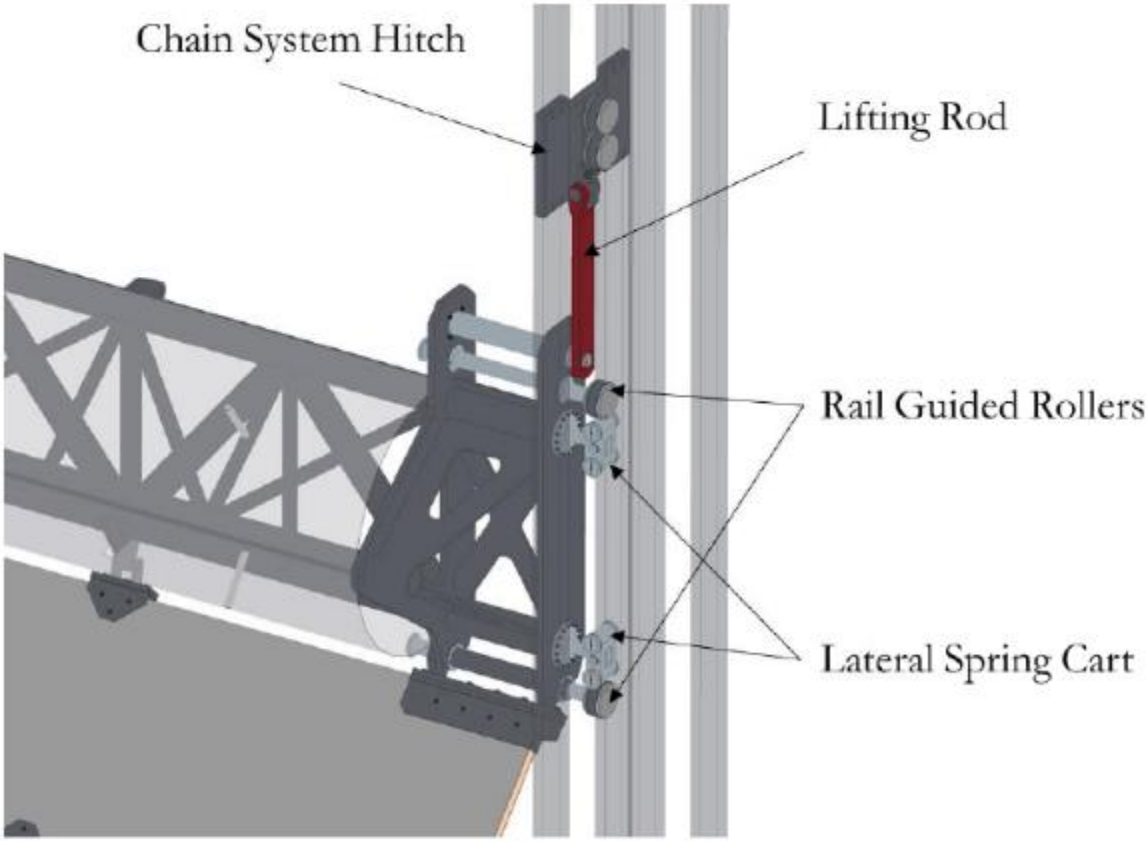

FIGURE 20: EWS LIFTING BEAM CONNECTION

The lifting beam connects to the chain drive using a lifting rod at either side of the screen. The lifting beam is a triangular truss covered to provide better aerodynamic properties. Each end of the lifting beam is equipped with springs acting in the direction of the main tubes to center the screen between the columns. Guide rollers are installed at the connections of each panel to control motion normal to the screen.

Tie rods transmit vertical load to the screen from the lifting beam allowing it to deploy. As the lifting beam raises the tie rods transmit the weight of the panels below them. In order to avoid kinematic singularity, the tie rods have a hard stop that prevents them from fully deploying. This ensures predicable deployment behavior. The hard stops are equipped with shock absorbers to prevent impact loads.

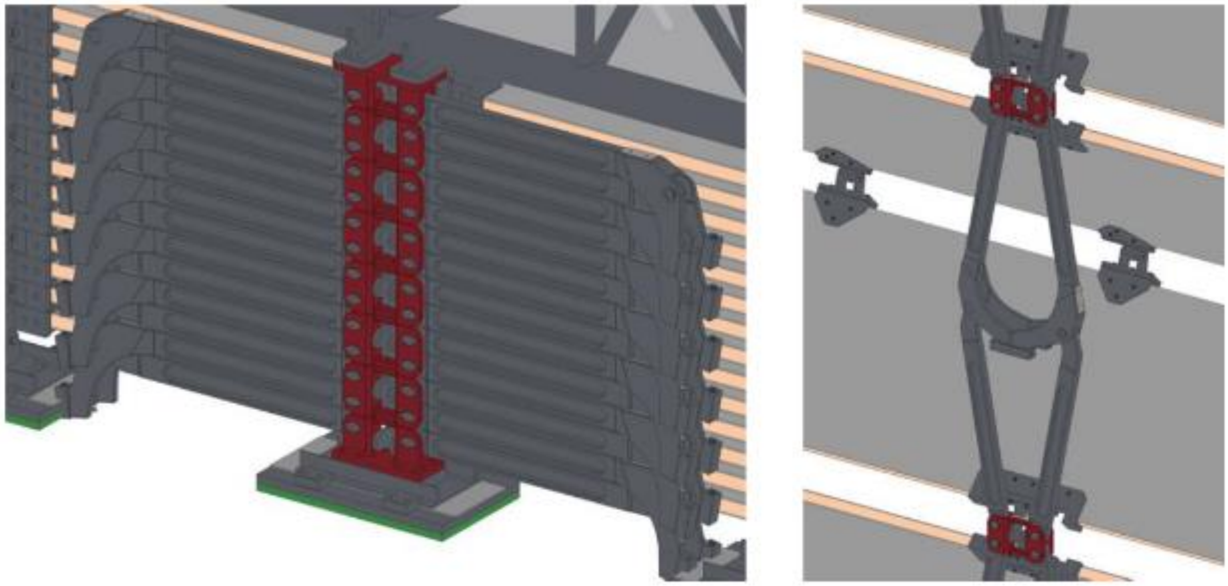

FIGURE 21: TIE RODS IN STACKED AND UNSTACKED POSITION

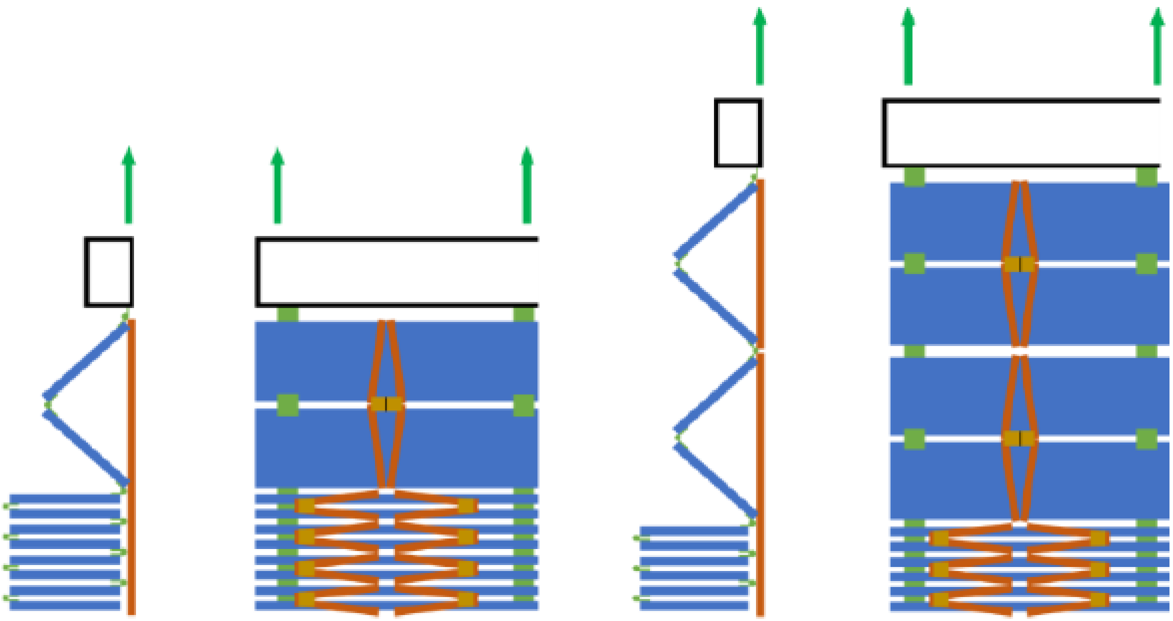

FIGURE 22: TIE ROD DEPLOYMENT

The EWS is lifted using two symmetrical, closed loop, chain hoists mounted to columns at either side of the screen. The driven sprockets are at the bottom of the columns for easy access and control of waste heat. These sprockets are driven by a pair of gearmotors on a common shaft. The return sprockets are at the top of the columns with a chain tensioning system. The hoist is counterweighted and designed to have a slight imbalance with the screen always tending to lower.

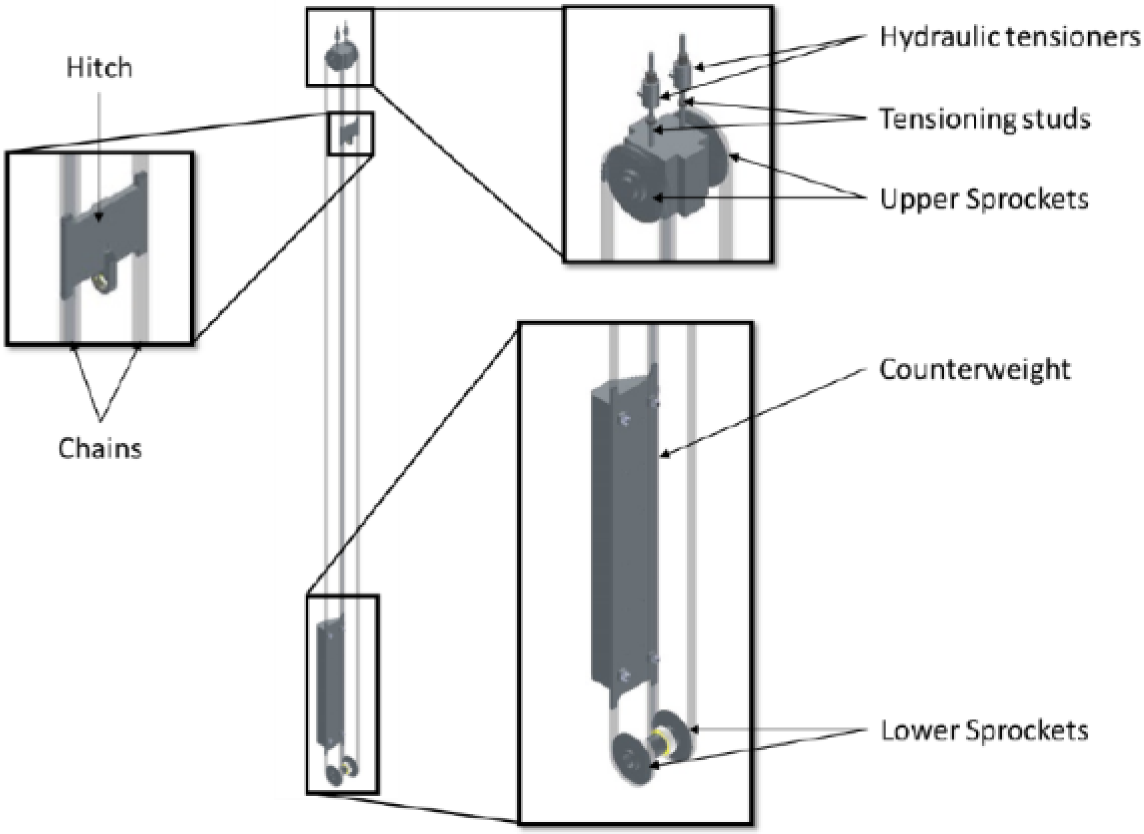

FIGURE 23: EWS CHAIN HOIST

The counterweight center of gravity is not aligned with the chain axes; therefore, a guiding system is included to absorb all off axes loads, enabling the chain to absorb only loads in its axes.

FIGURE 24: EWS CHAIN HOIST OPERATION

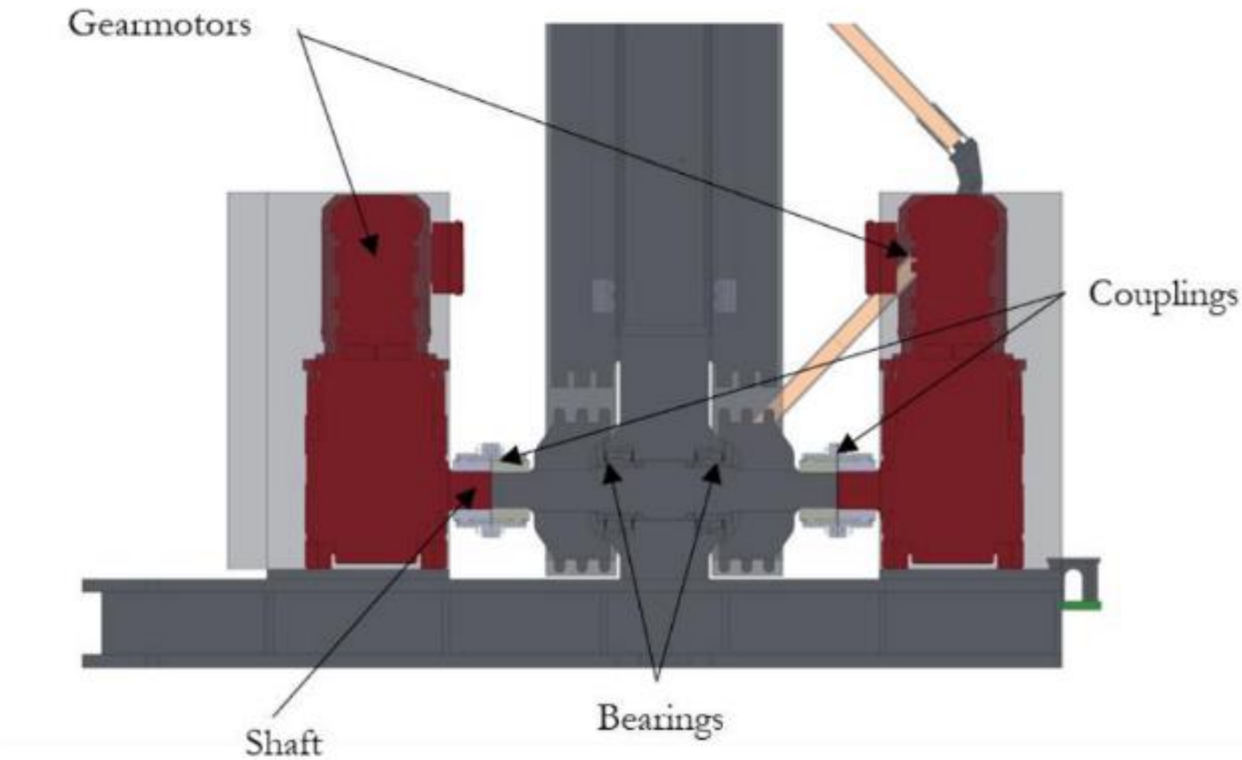

FIGURE 25: CHAIN HOIST GEARMOTORS

Cladding, Wind Vents and Sealing

The Enclosure must prevent infiltration of water, dust, snow, air, UV radiation and daytime light. To minimize infiltration, joints between moving portions of the Enclosure must be effectively sealed. The sealing system between the Upper Enclosure, Lower Enclosure and Bi-Parting shutters uses two layers of protection: a lip seal outside and an inflatable seal inside. At the roof seals, there is an additional gutter to add an extra layer of protection over the telescope.

A modular cladding system has been selected for the vertical walls of the Enclosure to minimize leakage. The surface of the Upper Enclosure is covered with an array of roll up doors called wind vents. These wind vents allow natural ventilation of the Enclosure in order to equalize temperature with the environment at night. The wind vents are integrated into the panel system and can be easily transported to the summit in standard 40’ shipping containers.

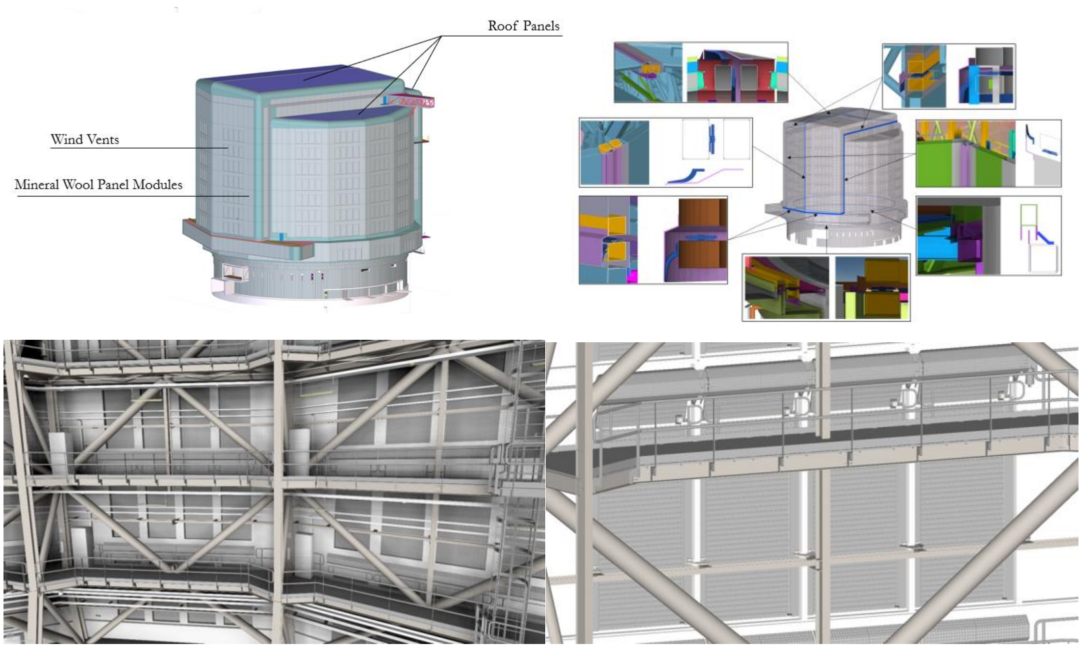

FIGURE 26: CLADDING, WIND VENTS AND SEALING

Controls

The Enclosure will include an Enclosure Device Control System (EDCS) to control and monitor the enclosure rotation system, bi-parting shutter, wind vents, wind screen, pier lift platform, floor hatch, upper enclosure lights, bridge crane and seismic isolation system. Also, the Device Control System will monitor the status of the upper enclosure elevator. The Enclosure Device Control System interfaces to the Observatory Control System (OCS) to allow science operations.

Enclosure Control and Safety System is responsible for the implementation and execution of the control and safety functions related with the Enclosure Mechanisms, Enclosure Utilities, Building Automation System and Power Management System to allow the correct operation and performance of the Enclosure subsystems and ensure the safety conditions for the personnel and equipment during the operation.

The control functions of each GMT subsystem are implemented in a Device Control System (DCS). The Device Control System (DCS) is the electric/electronic system aimed to carry out the defined functional features and operation concepts.

In this two-tier deployment, the control function is divided into two parts, a High-Level Control tier which provides supervision functions and interfaces with the Observatory Control System (OCS), and the Low-Level Control tier, built using a PLC programming environment, which provides control functions, safety functions and interfaces with the controlled subsystem. Each DCS requiring implementation of functional safety has its own Local Interlock Safety System (ISS) controllers that shall implement all the local safety related control functions as derived from the Hazard Analysis.

Low-Level Controllers have their HW installed in distributed cabinets that are allocated in the different areas of Enclosure. For each subsystem Hardware design, commercial solutions for all the sensors and actuator, I/O modules, drive systems and PLCs have been selected, specifying the electrical interface and the connection type. Each field component signal has been defined with the connection to an I/O terminal using the selected Beckhoff hardware. The distribution of hardware components into different cabinets has been performed considering field components location and distribution.

Control strategies for the Motion subsystems controllers and the Utilities subsystems controllers have been defined. For each subsystem control strategy, the control deployment mode has been selected, stablishing where the control loops are performed (PLCs or drive systems), which parameters are used in the control loop (proportional gains, integral gains, etc.) and which field devices and signals are used to close the loop. For the most important motion systems (Enclosure Rotation System and Bi-Parting Shutters) a Simulink model has been performed to analyze the controllability of the system and test different control strategies.

Regarding the Enclosure Interlock and Safety System (ISS), the Safety Related Control Functions (SRCF) have been obtained from the hazard analysis establishing the functional requirements and Safety Integrity Level (SIL) according to the IEC 62061:2021 standard. Each SRCF has been divided into detection subfunction, logic subfunction and reaction subfunction following the guidelines defined in the standard.

Design validation

The design validation process has been performed using mathematical models, mockups and in some case early prototypes. These include:

- Integrated finite element models of the mechanisms and structures to validate the design under extreme and fatigue load cases including earthquakes and strong winds.
- Simulink models to verify control strategies considering the dynamics of the structures and mechanisms.
- Wind tunnel tests and CFD models to verify behavior under wind loads and adverse thermal conditions. The dynamic effects caused by wind buffeting over the structure in open and closed configurations have also been analyzed.
- A site-specific seismic hazard analysis (SSSHA) has been developed. The SSSHA comprises eleven records of ground motions in three directions, two horizontal and one vertical, spectrally

matched to conditional mean spectra of the site-specific probabilistic risk targeted maximum considered earthquake (MCE_R) response spectrum. A representative set of eleven subduction earthquakes were selected and spectrally matched over a period band between 0.01 to 10 seconds according to the selection and scaling requirements of section 16.2.3.3 of ASCE 7-22. The selection process considered the earthquake source and site characteristics as well as the duration and frequency of the records. Accelerograms whose response spectrum was more similar to MCE_R were preferred to minimize the required spectral matching. The records were selected from Next Generation Attenuation (NGA) Subduction Database and included six records from Chile, four from Japan and one from Peru. The MCE_R time series are used to verify the enclosure structure according to ASCE 7-22 standard requirements using non-linear models of the mechanisms, including hard stops, clearances, non-linear materials, among other effects and their interaction with the structure. The steelwork structure has been designed to remain in the elastic region to avoid damage and costly reparation causing long-term downtime. In addition, the structure has been designed to provide sufficient stiffness at interfaces with mechanisms to ensure their correct operation.

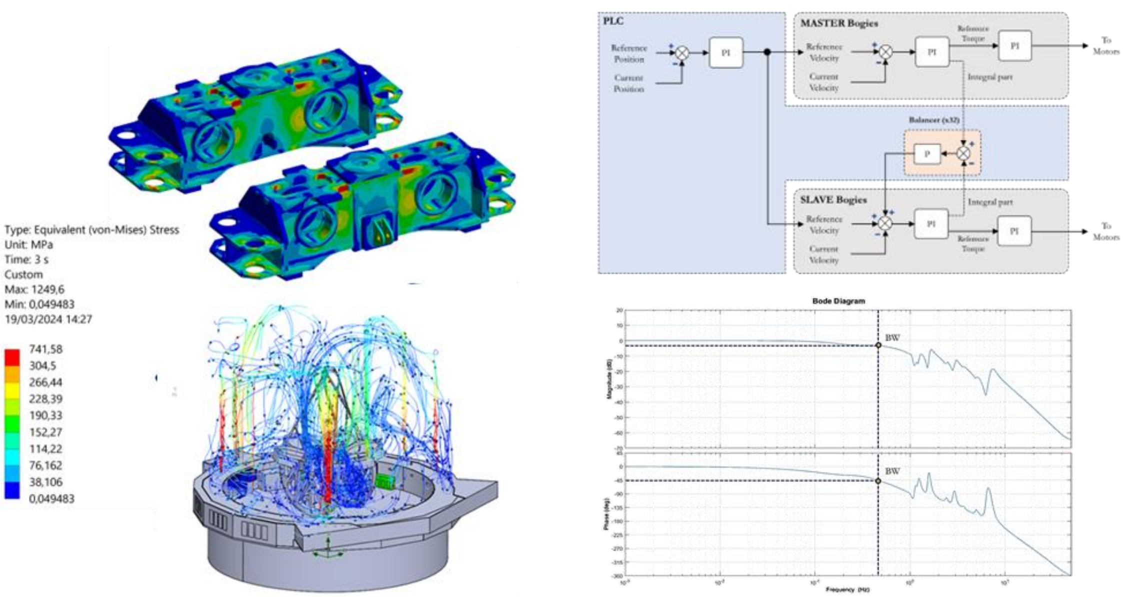

FIGURE 27: MATHEMATICAL MODELS FOR THE DESIGN VERIFICATION

- Mock-ups have been developed during the basic design stage to validate the kinematics and key functionalities of the major mechanisms, such as the ERS and EWS. Early unit prototypes have been tested during the detailed design phase to confirm key properties of some critical components.

FIGURE 28: MOCKUPS AND EARLY UNITS TESTS FOR THE DESIGN VERIFICATION

Constructability

One of the main design challenges of the GMT Enclosure is construction in a remote, high elevation, location with scarce resources and accessibility. With this in mind, components have been designed to be easily transported, lifted and assembled using a modular construction approach. Work needed on site has been minimized favoring shop assembly into the largest possible modules.

The construction sequences and tolerances, including leveling and adjustment means, have been defined to ensure the mechanisms and large structures work smoothly under the operational conditions and can survive the extreme working conditions.

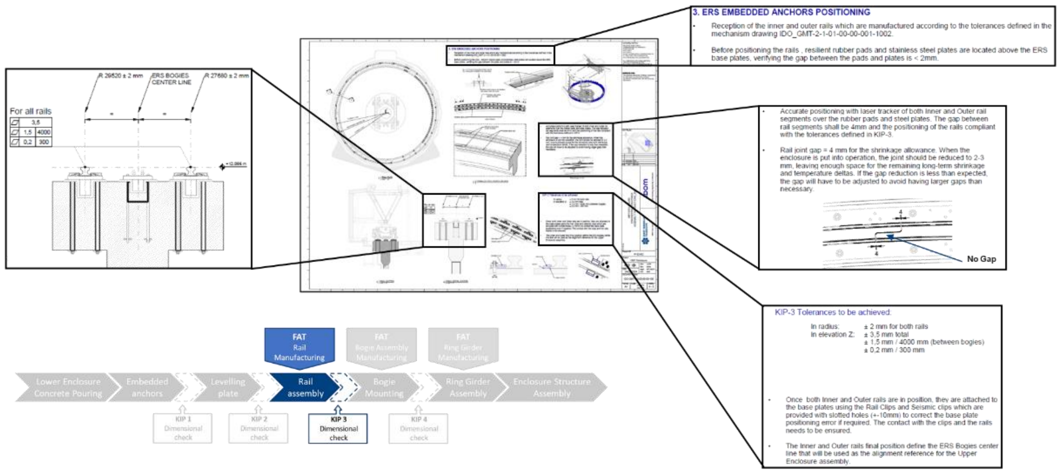

FIGURE 29: CONSTRUCTION SEQUENCES AND TOLERANCES DEFINITON

Conclusions

The GMT Enclosure design has just passed (May, 2024) its final design review and the construction procurement process is in the early stages. Over the next years, the construction contract will be awarded, and construction will proceed. In the short term, GMTO is planning a prototype fabrication and testing program for some the mechanisms, to reduce the risks inherent in the uniqueness of the design.

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