Electronics prototypes for the Giant Magellan Telescope Multi-object Astronomical and Cosmological Spectrograph (GMACS)

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ABSTRACT

We describe the current electronics prototypes for the Flexure Compensation System (FCS) and the Slit Mask Exchange Mechanism (SMEM) for GMACS, a wide-field, multi-object, moderate-resolution optical spectrograph for the Giant Magellan Telescope (GMT). We discuss the details of the FCS and SMEM prototypes, how the prototypes relate to the preliminary conceptual designs of these systems, and what information the prototypes give that can be applied to the final design, as well as the possible next steps for each prototype.

Keywords: multi-object spectrograph, GMACS, flexure compensation, slit mask, Giant Magellan Telescope

1. INTRODUCTION

This paper presents the preliminary electronics prototypes for the wide field, multi-object, moderate resolution, optical spectrograph, called GMACS. GMACS (Giant Magellan Telescope Multi-object Astronomical and Cosmological Spectrograph) is a first light instrument for the Giant Magellan Telescope (GMT). The most important factors for GMACS are its high throughput, simultaneous wide wavelength coverage, accurate and precise sky subtraction, moderate resolution, and wide field. Additionally, since it is expected to be one of the most used instruments on the GMT, the amount of time spent not collecting data should be minimized.

This paper focuses on the electronics prototypes for the mechanisms that optimize the simultaneous wide wavelength coverage, the wide field, and time spent not collecting data: the Flexure Compensation System (FCS) and the Slit Mask Exchange Mechanism (SMEM). The FCS and SMEM prototypes demonstrate how these subsystems work and what changes may need to be made to the subsystem designs. These prototype systems also allow us to develop general instrument control software and gain experience with the standard GMT control bus architecture.

To optimize the simultaneous wide wavelength coverage, a dichroic splits the light into two cameras, one for capturing redder wavelengths and the other for capturing bluer wavelengths. Figure 1 shows how light travels through the GMACS instrument, starting at the focal plane, splitting at the dichroic, and collected by a red-optimized camera and blue-optimized camera.[1]

To allow maximum observational flexibility, the resolution of the instrument can be changed between exposures. The instrument accommodates a range of spectral resolution and wavelength coverage for multiple targets positioned on a custom machined slit mask. Interchangeable gratings for each camera arm with different grating tilts and an adjustable collimator-camera angle accommodates both lower resolution and higher resolution modes.

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As the telescope rotates, the gravity vector acting on GMACS changes. The changing gravity vector causes the VPH gratings and camera arms to flex, which misaligns the optics and compromises the stability of science data obtained with the instrument. We currently anticipate that the Flexure Compensation System (FCS) will counteract this flexure with hexapods holding the collimator, gratings, and camera arms. The hexapods adjust the position of the gratings and camera arms with high accuracy and precision so that they are not misaligned.
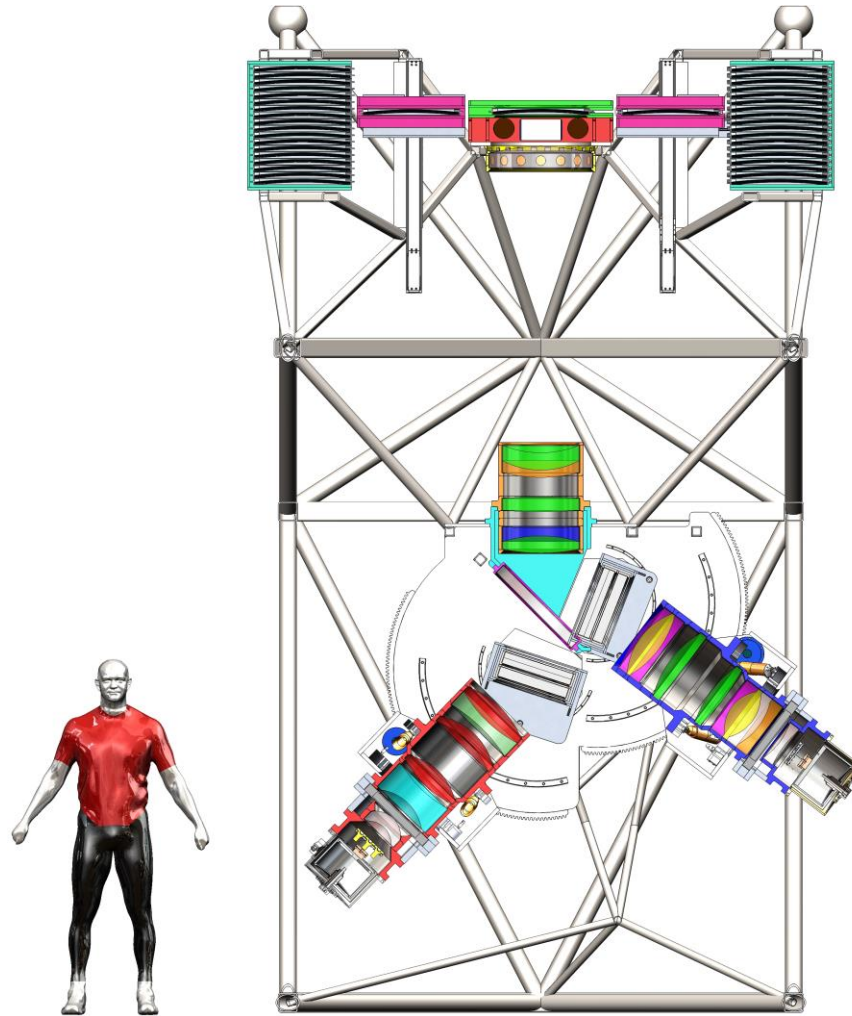

Figure 1. The current GMACS concept. Light enters the focal plane at the top of the instrument, passes through the collimator is split at the dichroic. From there, the light passes through VPH gratings and the red and blue camera arms.

To minimize time spent not collecting data, the slit masks can also be changed between exposures. The cassette-like Slit Mask Exchange Mechanism (SMEM) retrieves the current slit mask in the focal plane, returns it to the slit mask magazine, retrieves the next slit mask from the magazine, and places the next slit mask in the focal plane. This can be done without human intervention between observations and while the telescope is moving.

To develop general instrument control software and gain experience with the standard GMT control bus architecture, both prototypes are controlled through EtherCAT, which is the communications protocol that controls GMT and the GMT instruments. EtherCAT is an Ethernet based protocol that connects hardware devices such as motor drives and sensors to the fieldbus via input/output modules.[2] For the GMACS prototypes, a Beckhoff CX2020 CPU runs TwinCAT 3.0 to control the modules as an EtherCAT master, and several types of Beckhoff modules connect to the sensors, motors, and other hardware for each prototype. Additionally, the FCS and SMEM prototypes are good platforms for practicing software integration between the GMACS electronics and software teams.

2. FLEXURE COMPENSATION SYSTEM (FCS) PROTOTYPE

2.1 FCS conceptual design

Under normal conditions, large structures experience some flexure under the structure's own weight. This flexure can usually be predicted and accounted for. However, as the GMT rotates and changes position, the gravity vector on GMACS will change. This changing gravity vector will cause the instrument's flexure to change, as shown in Figure 2. If the instrument's flexure changes, the optics become misaligned.[3]
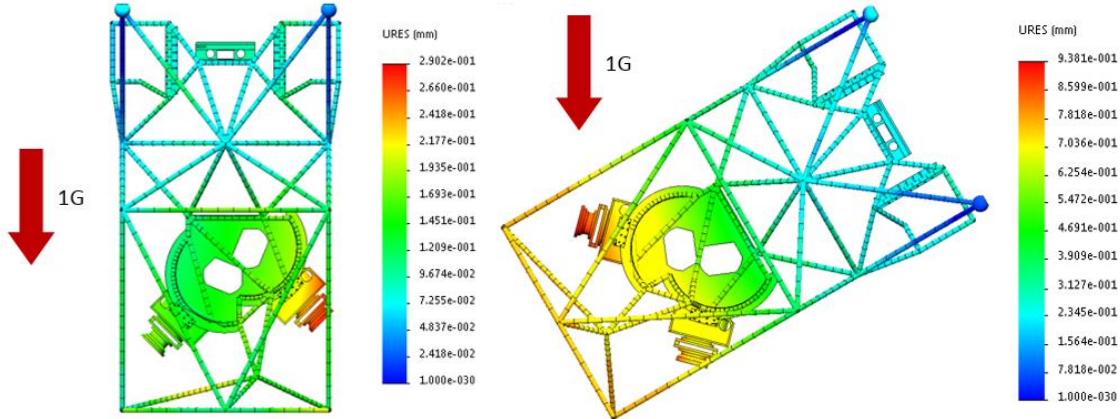

Figure 2. The flexure of GMACS at zenith and when the GMACS is rotated 60 degrees about the X axis. The instrument and camera arms are affected by gravity, forcing the optics out of alignment.

To maintain the optics' alignment, the flexure must be compensated. The positions of the focal plane, VPH gratings, and camera arms need to be adjusted slightly during telescope operation to stay aligned. The FCS mounts the VPH gratings and camera arms to hexapods that can adjust the positions of the VPH gratings and camera arms in 6 dimensions. The custom hexapods are large enough to encompass the VPH gratings and camera arms and have micrometer precision.

We currently expect that positional feedback to the control system for the hexapods will come from lasers mounted on the VPH gratings and camera arms and pointed at lateral sensors. The lateral sensor measures the displacement of the laser beam relative to the center of the sensor. The sensor returns the X and Y position of the laser beam, and the hexapod moves to recenter the beam.

2.2 FCS prototype construction

Physik Instrumente lent an H-840.D2 hexapod, shown in Figure 3, with an EtherCAT slave controller. The EtherCAT slave controller takes motion commands from the EtherCAT master PC and translates them into movements of the individual hexapod actuators. The Beckhoff EtherCAT master PC runs Beckhoff TwinCAT 3.0, and the written program is controlled by the user through a TwinCAT GUI.

A Thorlabs PDP90A lateral sensor is mounted to the hexapod, and a 5 mW 632.8 nm laser points at the center of the lateral sensor, shown in Figure 4. The prototype setup is similar to the lasers and sensors that could be on the GMACS instrument, with the hexapod body encompassing the optics of the VPH gratings and camera arms.

The laser shines on the lateral sensor, and the sensor sends the position of the beam to the EtherCAT master PC as two analog signals, one for the X-axis and one for the Y-axis. The analog signals are read by the EL3002 Beckhoff 2-channel analog input terminal, shown in Figure 5, and the position of the beam is calculated and displayed by the program. The program commands the hexapod to move to return the laser beam to the center of the lateral sensor.

To test the prototype, the laser is mounted to an optical mount that can be slid back and forth manually. The tester moves the laser less than 2 mm to the left and right, the beam shines on the lateral sensor to the left or right of the center, the sensor sends the X and Y coordinates to the EtherCAT master PC, and the EtherCAT master PC commands the hexapod to move to recenter the beam. The laser can be aimed 2 mm up and down for the same effect, causing the hexapod to move up and down. Figure 6 shows the entire prototype setup.

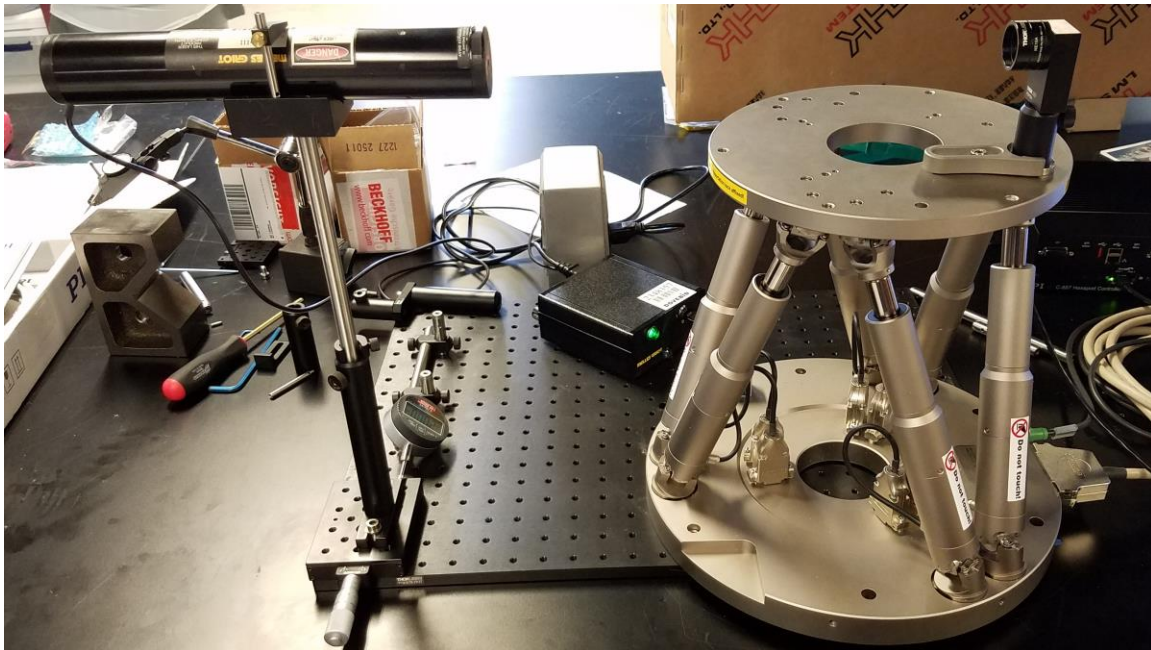Figure 3. Physik Instrumente H-840.D2 hexapod

Figure 4. FCS prototype test setup, with the laser on the left and Thorlabs PDP90A lateral sensor on the right
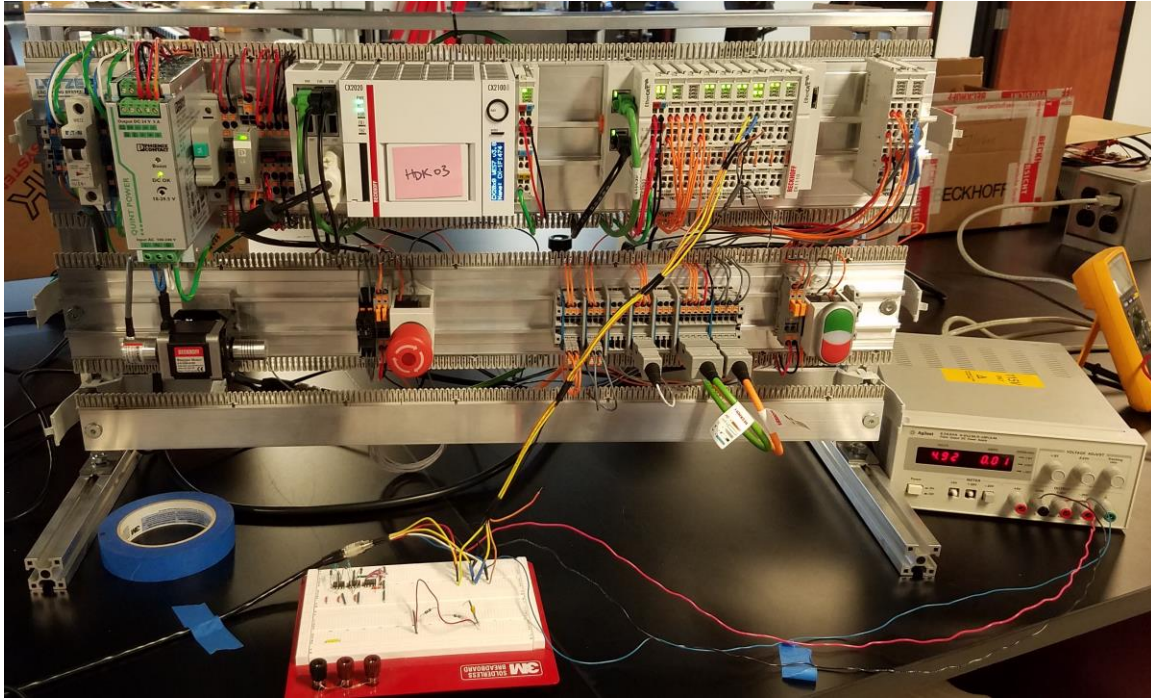
Figure 5. The Beckhoff CX2020 EtherCAT master PC and Beckhoff EtherCAT terminals. The EL3002 reads the analog outputs of the lateral sensor, and the power supply supplies about 5V to the lateral sensor
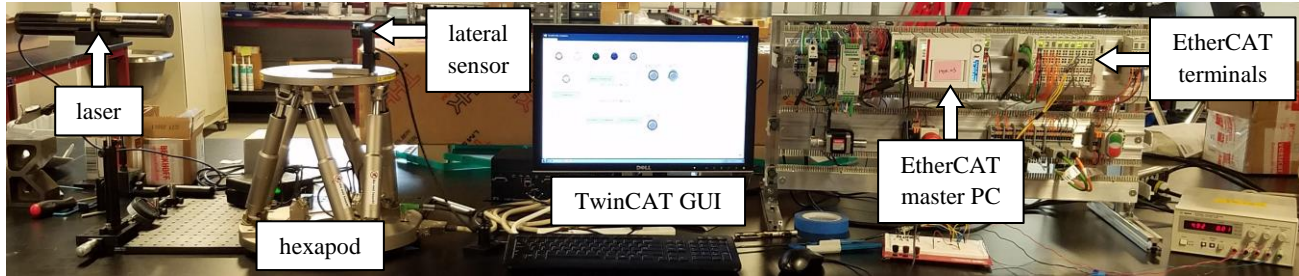

Figure 6. The entire FCS prototype. On the far left, the laser is mounted to a sliding optics rail that is moved manually, and the laser is pointed at the lateral sensor that is mounted on top of the hexapod. The TwinCAT GUI allows the tester to move the hexapod, see what position the lateral sensor reports, and see the current position of the hexapod. The EtherCAT master PC reads the analog signals sent to the EL3002 2-channel analog input terminal and sends commands to the hexapod controller.

The TwinCAT hexapod control program is built with several function blocks from the TwinCAT motion control library, shown in Figure 7. The function blocks can read the position of each hexapod axis, move each axis to an absolute position, and move each axis a relative amount. The positions of the hexapod axes are displayed on the GUI, shown in Figure 8, the absolute motions can command the axes to return to zero or any other position, and the relative motions are used to move the hexapod the distance reported by the lateral sensor to return the laser beam to the center of the lateral center.
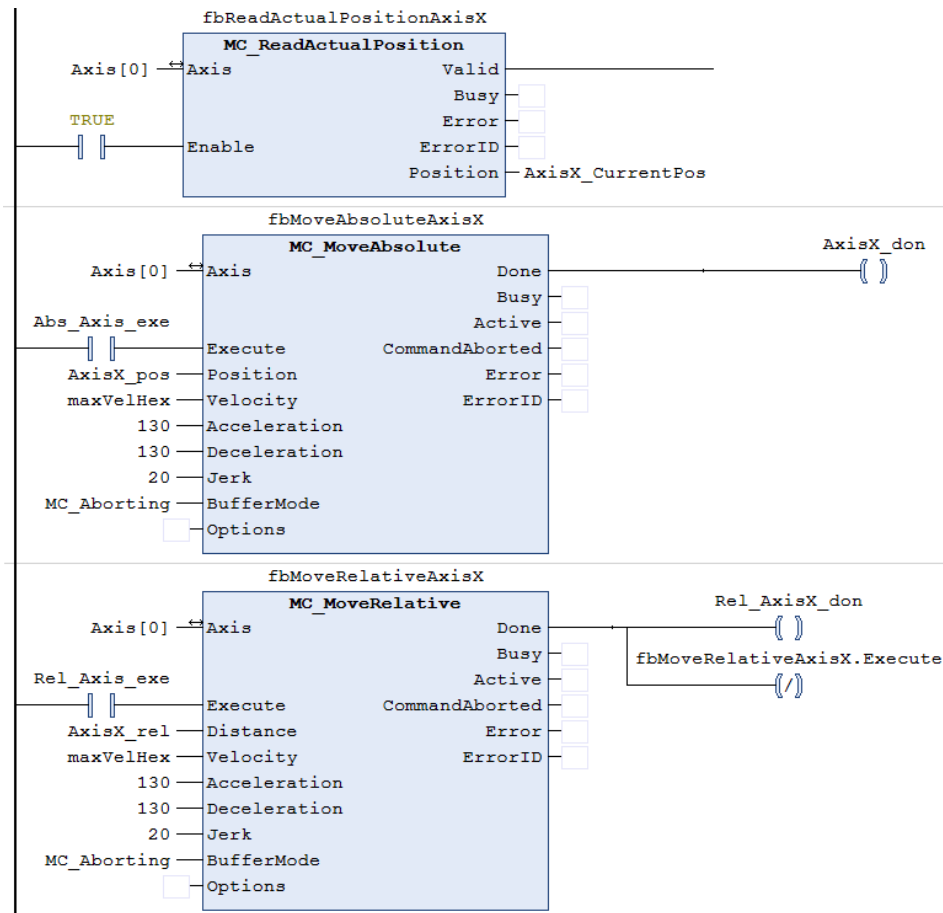
Figure 7. Function blocks read the hexapod's position and move the hexapod axes to an absolute position or relative distance.
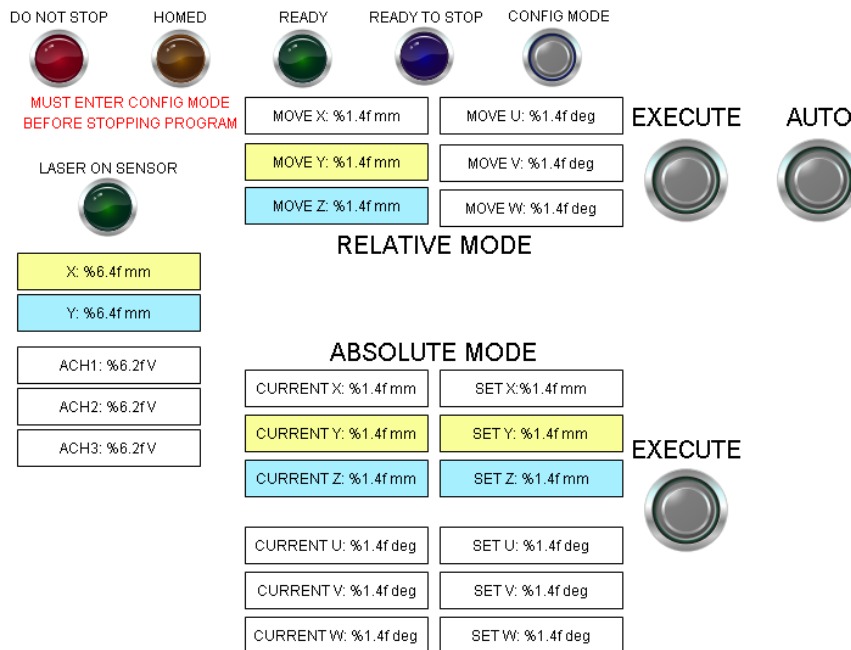

Figure 8. FCS TwinCAT GUI. The highlighted sections are the axes of the lateral sensor that correlate to the motion of the hexapod.

2.3 FCS prototype results

When the tester moves the laser left or right, the hexapod moves automatically to recenter the beam on the sensor, shown in Figure 9. One problem with the test is that if the hexapod begins moving before the laser has stopped moving, the hexapod moves to the position the sensor reported just before the hexapod started moving. The hexapod then stops, receives the final position of the beam, and moves again to finally correct the beam location. This happens because the motion commands are buffered, causing the first motion command to complete before any others are executed. The solution to the problem is to make sure new motion commands cause old motion commands to be aborted. While time was not on our side to implement this solution, knowing this issue will help with the next FCS prototype.

Additionally, a dial gauge was attached to the hexapod, and the hexapod was commanded to move in the Z-direction 10 micrometers. The hexapod is able to move 10 micrometers reliably according to the dial gauge, which is the amount of precision required to correct misalignments in the optical path on GMACS.

Figure 9. The laser beam is centered in the first panel, off-center in the second panel, and centered again in the third panel after the hexapod adjusts the lateral sensor's position.

2.4 FCS prototype next steps

Possible next steps for the FCS prototype include Physik Instrumente designing a hexapod capable of holding the GMACS optics and the GMACS team deciding how the laser beam will interact with the optical path or implementing a different method for positional feedback. The next prototypes need to test the hexapod handling the torque and weight of a camera arm and integration with the GMACS software team's user software.

3. SLIT MASK EXCHANGE MECHANISM (SMEM) PROTOTYPE

3.1 SMEM conceptual design

The Slit Mask Exchange Mechanism (SMEM), shown in Figure 10, is a jukebox style mechanism that retrieves slit masks from the focal plane, places the slit masks in an empty slot in the magazine, retrieves the next slit mask, and places it in the focal plane. To accomplish this, the SMEM has two vertical linear actuators (VLA) that raise and lower the elevator that houses the slit mask in transit. The horizontal linear actuator (HLA) moves the slit mask from the magazine to the elevator and the elevator to the focal plane. On the HLA is a grabber that retrieves the slit mask from the slit mask magazine. The slit mask magazine can be accessed by technicians to load slit masks for the whole night of observations, ensuring there is no telescope downtime.
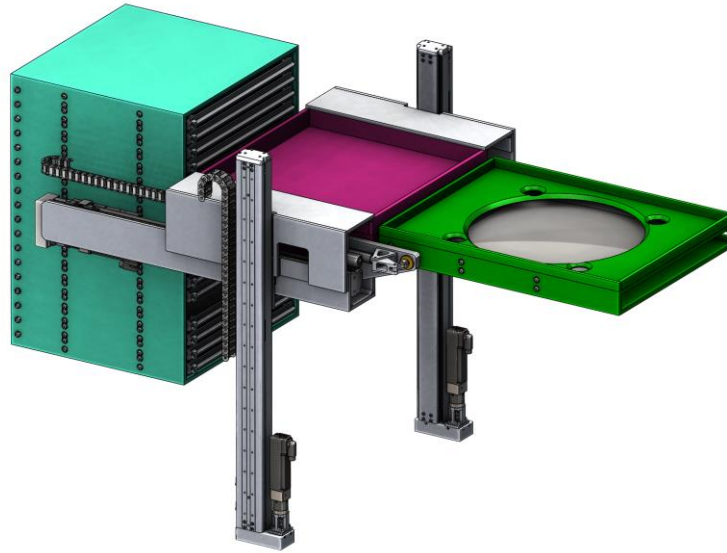

Figure 10. The Slit Mask Exchange Mechanism includes two vertical linear actuators (VLA), one horizontal linear actuator (HLA), a grabber on the HLA, and the slit mask magazine that can be accessed by technicians.

3.2 SMEM prototype construction

The SMEM prototype is a 90% scale of the horizontal portion of the slit mask elevator, shown in Figure 11. The gap simulates the gap between the slit mask magazine and the slit mask elevator, which the rollers on the slit mask holder will have to overcome. The slit mask holder is mounted on a cart that slides on a THK linear actuator, shown in Figure 12. The THK linear actuator is powered by a Beckhoff motor controlled by a Beckhoff EtherCAT terminal that communicates with the Beckhoff EtherCAT master PC, shown in Figure 13.
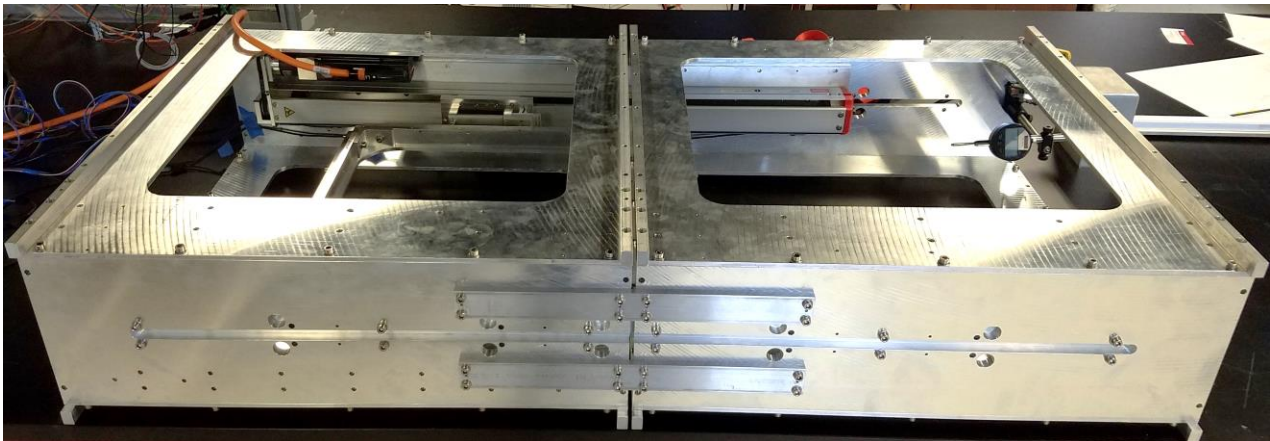

Figure 11. The SMEM prototype with a THK rail and Beckhoff motor.

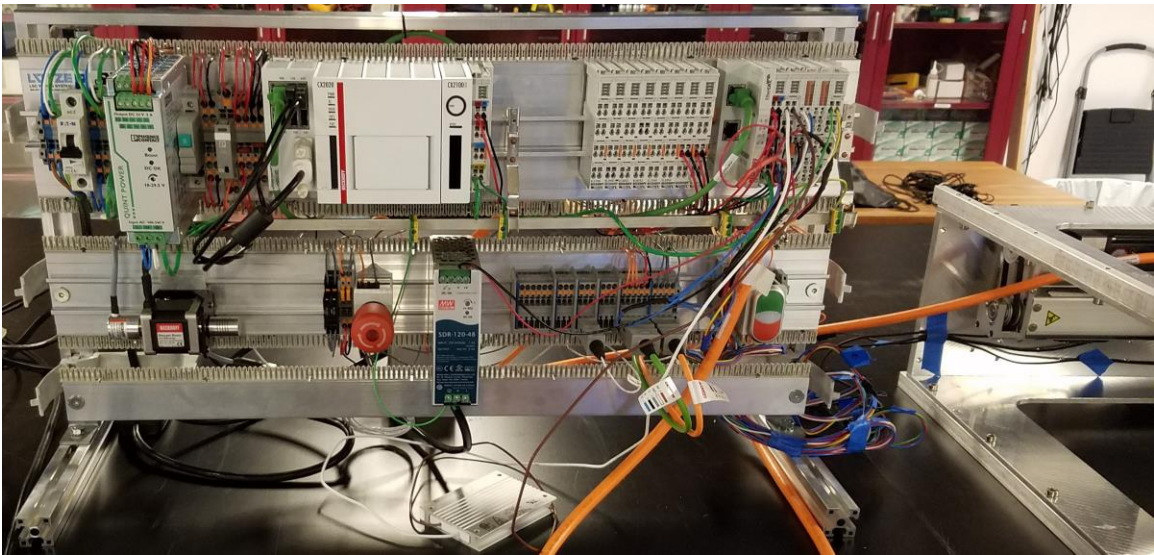Figure 12. The Beckhoff motor and the THK rail cart.

Figure 13. The EtherCAT master PC and EtherCAT slave terminals that control the Beckhoff motor and read the limit switches on the THK linear actuator.

Controlling the Beckhoff motor is similar to controlling the hexapod with motion function blocks, shown in Figure 14. For the SMEM prototype reliability test, the cart moves the slit mask holder from one end of the SMEM prototype frame to the other repeatedly. The function blocks read the current position of the cart, move the cart to the far end of the SMEM prototype frame, waits for a user-defined time to allow the cart to settle, then returns to its starting position.

The SMEM prototype can be controlled by a user through two GUIs, one created in TwinCAT and one created in Visual Studio C++. The TwinCAT GUI, shown in Figure 15, allows the user to home the linear actuator cart, move the cart to an absolute position or a relative distance, read the current position of the cart, and monitor the home and limit switches. The user can also start the repeating slide sequence to test the reliability of the SMEM prototype.
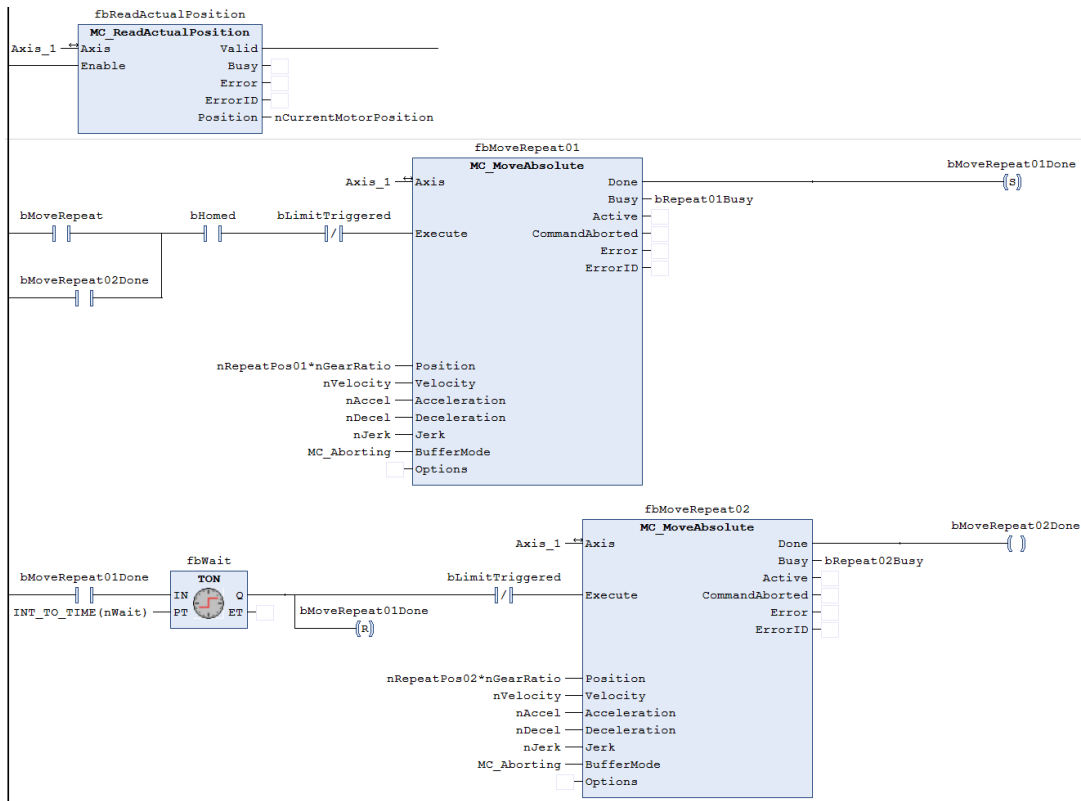
Figure 14. Function blocks read the current position of the linear actuator cart and move the motor to an absolute positions.
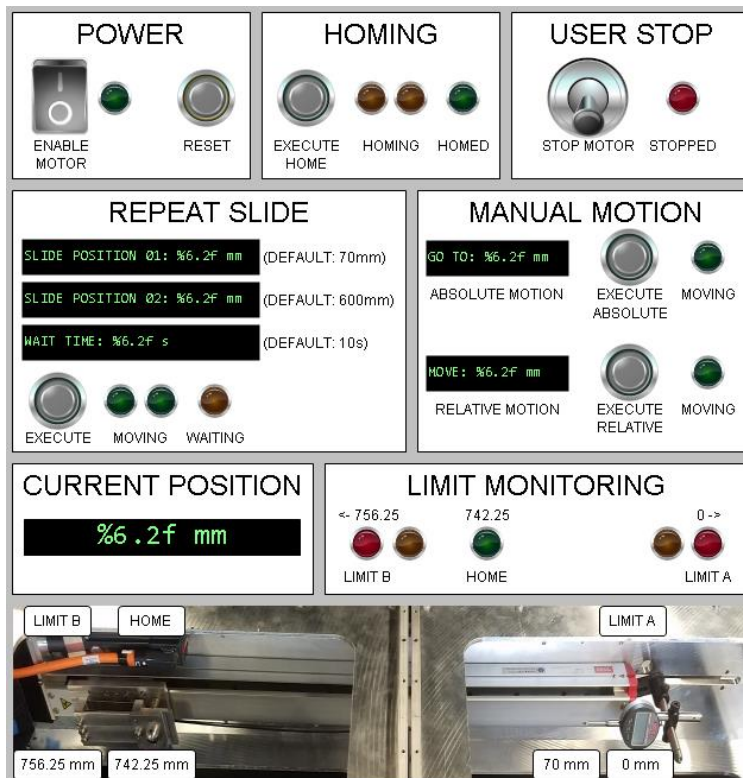

Figure 15. SMEM TwinCAT GUI

The Visual Studio C++ GUI created by the GMACS software team, shown in Figure 16, communicates with the EtherCAT master PC through TCP/IP. The user can connect their PC to the EtherCAT master PC through a regular Ethernet cable and control the SMEM prototype with the same commands as the TwinCAT GUI. Additionally, the user can write and load a script of power, homing, and motion commands that the Visual Studio C++ program will execute automatically. Integrating the TwinCAT control and the Visual Studio C++ GUI is a preliminary step for the GMACS electronics and software teams to practice integrating their portions of the GMACS subsystems' software.
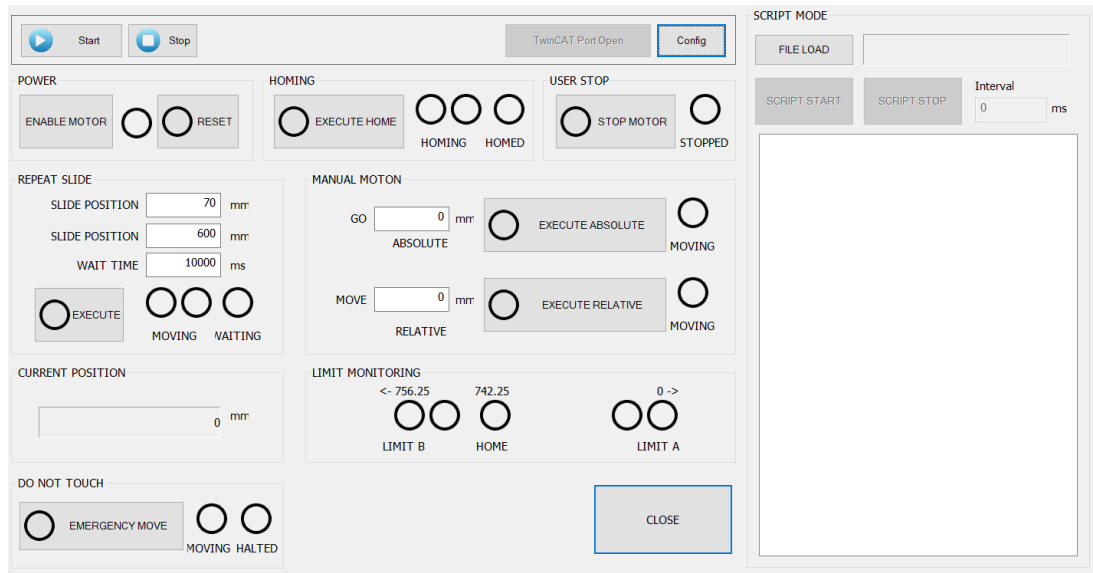

Figure 16. SMEM Visual Studio C++ GUI

3.3 SMEM prototype results

The SMEM prototype tests the reliability of the motion of the THK linear actuator while the slit mask holder is attached to it. A dial gauge is attached to the far end of the SMEM prototype, measuring how far the slit mask holder presses the dial gauge when it travels to the end of the rail. After observing the motion about 20 times, there is only slight drift in the return position, on the order of micrometers.

To simulate the changing gravity vector, the SMEM prototype was ran in several different orientations. When rotated 90 degrees along the traveling axis, as shown in Figure 17, the reliability remains the same. When rotated 90 degrees orthogonal to the traveling axis, as shown in Figure 18, the leading roller is caught in the gap between the two sections when the slit mask holder travels upward. The problem persists when the angle is lowered to 60 degrees and 45 degrees. The slit mask holder needs to be redesigned so that the leading roller does not get caught in the gap.

Figure 17. The SMEM prototype rotated 90 degrees along the traveling axis

Figure 18. The SMEM prototype rotated 90 degrees orthogonal to the traveling axis.

3.4 SMEM prototype next steps

To test more design aspects of the SMEM, the next steps are to add linear encoding for more reliable position feedback, mount half of the current SMEM prototype to two vertical linear actuators (VLAs) and to prototype the slit mask grabber design.

Linear encoders use a strip of magnetic or optical encoding along a flat surface that is read by a sensor that would be mounted to the moving cart. For the SMEM, the encoding is magnetic rather than optical to avoid stray light. The advantages of using linear encoders are immunity to gear slew and high resolution.

Mounting half of the current SMEM prototype to two VLAs will test the ability of the VLAs to raise and lower the slit mask holder. The two VLAs must move in perfect unison to move the slit mask holder to the slit mask slots in the slit mask magazine and back to the focal plane. Programming a gantry mode for the motion commands ensures that the VLAs have identical movements.

The slit mask grabber attaches to a slit mask from the magazine and pulls the slit mask into the slit mask holder as the horizontal linear actuator (HLA) moves the grabber. One possible design is to have the HLA move back and forth twice. The grabber attaches to the leading side, the HLA pulls the mask halfway into the slit mask holder, the grabber releases, the HLA moves back to the magazine so the grabber can attach to the trailing side of the slit mask, and the HLA moves back to the slit mask holder to fully place the slit mask into the slit mask holder.

4. CONCLUSIONS

GMAC's prototypes inform the evolving design of GMAC's subsystems. The Flexure Compensation System ensures the optics stay aligned, and mounting the optics on hexapods is the current design concept. The FCS prototype proves that hexapods have the precision required for the needed slight adjustments and that programming the hexapod's movements using TwinCAT or possibly another EtherCAT program is straight forward. The Slit Mask Exchange Mechanism cycles the slit masks required for observation throughout the night without any telescope downtime. The SMEM prototype reveals the necessary changes to the mechanical design and provides a platform on which the electrical team and software team can practice integrating their subsystem programs. Improving the prototypes and the mechanical, electrical, and software designs is an iterative process for the FCS, SMEM, and other GMACS subsystems.

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