The aim of this project is to continue the development of an automated telescope and dome to support star and satellite tracking operations. SEIT at UNSW Canberra maintain a dome and telescope system installed on the roof of building 16, as well as portable amateur telescopes, and the Falcon Telescope. This project will modernise the systems by implementing modern microcontroller integration to the existing systems and creating additional required subsystems. The project includes advances to the systems that include motion logging, to provide advanced image capture quality. The result is a bespoke computer-controlled telescope created as a proof of concept, the roof telescope operating with increased functionality, then previously capable, and options for different drive control, and a repaired Meade LX200 portable telescope. All are supported by variations of a software driver allowing for integration with planetarium and satellite tracking software.

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1 ASLT RAN, School of Engineering & Information Technology. ZEIT4500.
### Nomenclature

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<th>Acronym</th>
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<tr>
<td>ALT</td>
<td>Altitude</td>
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<tr>
<td>ASCOM</td>
<td>Astronomy Common Object Model</td>
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<tr>
<td>AZM</td>
<td>Azimuth</td>
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<tr>
<td>COTS</td>
<td>Commercial Off The Shelf</td>
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<tr>
<td>DEC</td>
<td>Declination</td>
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<tr>
<td>DOF</td>
<td>Degrees Of Freedom</td>
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<td>FTM</td>
<td>Flexi Timer Module</td>
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<tr>
<td>FTN</td>
<td>Falcon Telescope Network</td>
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<tr>
<td>GEM</td>
<td>German Equatorial Mount</td>
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<tr>
<td>GOTO</td>
<td>Go To co-ordinate</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>I2C</td>
<td>Inter-Integrated Circuit Bus</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
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<tr>
<td>IRLED</td>
<td>InfraRed Light Emitting Diode</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
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<tr>
<td>MEMS</td>
<td>Micro Electro Mechanical System</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PEC</td>
<td>Periodic Error Correction</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
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<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
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<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
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<tr>
<td>RA</td>
<td>Right Ascension</td>
</tr>
<tr>
<td>SPI</td>
<td>Serial Peripheral Interface Bus</td>
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<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
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1° = 1 Degree  
1′ = 1 Arc Minute (60 Arc Minutes = 1 Degree)  
1″ = 1 Arc Second (60 Arc seconds = 1 Arc Minute)

### I. Introduction

UNSW at Canberra uses telescopes for a variety of research purposes. Two of the telescope mounts are not currently in use due to either a breakdown of components or outdated systems. The focus of this project is the application of engineering techniques to provide a method to control the different motor systems available on the telescope mounts. This motor control will be extended to include a software driver enabling telescope mount control with modern astronomy software.

#### A. Project Scope

The scope of this project is to investigate, design and create solutions enabling the use of astronomy equipment. Image capture will be used to verify mount positioning accuracy, but any analysis of astrophotography techniques remains beyond the scope of this work. The project is based on the work conducted on three different telescope systems. The first telescope is a small amateur astronomy telescope [1]. This system was used as a proof-of-concept whereby a Dobsonian style mount would be converted into a GOTO and automatic tracking telescope. The second telescope mount is housed inside a dome and located on the roof of building 16. This system, currently fitted with a 0.4m Meade Cassegrain telescope, previously provided opportunities for a variety of space surveillance research and observations [2]. In recent years the difficulties in using the system, compared to the acquisition of modern equipment, has seen its obsolescence. The exact condition of the equipment at project commencement was unknown. The third telescope is a Meade LX200 mount, fitted with a Meade 0.3m Cassegrain
telescope [3]. Prior to project commencement, the telescope developed a fault resulting in damage to the control board. The scope of this project is to both enhance and return to function, these latter telescope systems.

**B. Aim**

The project aims to enable the telescope systems to be used for research. This requires the systems to be used with current planetarium and satellite tracking software in use at UNSW [4,5]. This will require control systems that meet ASCOM standards for USB communications enabling use by both Windows and Macintosh operating systems [6]. The telescopes must be easier to use than the previous systems, which saw their obsolescence. These changes will include USB connectivity for modern PC’s, the ability to quickly reset pointing inaccuracy, via a home function, tracking rate control and accuracy improvements. An Inertial Measurement Unit (IMU) will also be fitted to investigate its feasibility as an actuator for future work [7].

**II. Literature Review**

The literature review covers the broader elements of the project. The review includes the OnStep driver chosen for telescope automation. A baseline of the condition of the telescope systems, referencing past work, is also covered. The potential use for the IMU completes the review.

**A. OnStep**

A method was required to connect the telescope mount hardware to the most common planetarium and satellite tracking software. After a review of several solutions, OnStep was chosen for its open source nature, configurability and LX200 emulation with ASCOM compliance. The level of these features, alongside a history of proven performance, placed it above other solutions [8]. OnStep is designed to utilise common stepper motor drivers and stepper motors to provide GOTO and tracking functionality to amateur telescopes. It achieves this through installation on Arduino based microcontrollers, this gives an opportunity to include extra features. OnStep acts as an interface between the astronomy software on a computer and the hardware platform, usually consisting of a microcontroller with stepper motor drivers and stepper motors. From the user perspective, the telescopes will operate similarly but achieve the outcomes differently. The OnStep driver is configured to match the hardware options of the telescope mount. Knowing the gearbox, stepper motor and micro-step resolution of the mount allows GOTO movements with dead reckoning and open loop tracking of objects. The ability to synchronise the mount position with planetarium software and adjust position or track speed with visual confirmation, allows users to close the loop.

**B. Roof Telescope**

Upon project commencement an examination of the state of the telescope mount and dome was undertaken. The purpose of the examination was to establish the baseline of the system and determine a functioning benchmark, to better define the scope of the project.

The telescope dome requires hand operation for rotation and opening, or closing, of the dome shutter. The dome is in full working order and further examination is covered in a later section of this report. The telescope mount is described by the block diagram shown in Fig. 1. Documentation from previous projects show the inclusion of an EZI-USB microcontroller setup however no such system was evident [9]. Previous use of the telescope indicated problems accurately tracking satellites due to the large step size. The combination of harmonic gearbox (200:1 reduction) and stepper motor (200 steps or 1.9° per step) and micro-stepping at a 1/8th rate provided a step size, in both RA and DEC, of 4.05”. This step size was previously determined as too large for accurate satellite tracking [10]. The mount currently features a unique stepper motor control system referred to as the ‘yellow box’ [11]. This system was designed in 1991 and consists of PBL3771 Precision Stepper Motor Drivers coupled with PBM3960 Micro-Stepping Controllers [12,13]. This system was originally designed to allow for micro-stepping the stepper motors at 1/1024th. This micro-stepping is achieved by controlling two sine waves.
providing power to the windings of the motors with the use of a PLL. By controlling the speed and current supplied, the step rate can be controlled. The current is adjustable through 128 levels per winding to provide the 1024 micro-steps. When combined with the 200:1 reduction gearbox, and 200 step motors, the smallest telescope movement possibly available in both RA and DEC will be ~0.03°. This system was originally designed to be operated by a parallel data bus connection to a computer. A Teensy 3.0 microcontroller has been installed to act as a USB serial to parallel adapter.

The Teensy 3.0 microcontroller code [14], for the yellow box, and a MATLAB GUI code [15], for communicating with the microcontroller, are required for mount movement. The MATLAB GUI provides the data words to the Teensy selecting motor, rate, direction and start or stop, see Fig. 2. The Teensy microcontroller code acts as an interface between a computer’s USB and the parallel port of the yellow box. Tests with the system proved that movement in both RA and DEC under different speeds is currently possible. The system allows for control of the step rate (speed) in both RA and DEC. This is done by providing the N and P words used in equation (1).

\[
\text{Step Rate} = \frac{N}{2^P} \times 16MHz
\]  

(1)

This made it possible to drive the mount to an approximate location before locking the RA for sidereal rate to allow for star tracking. Small movements in any direction are achieved by sending a move command, at the minimum speed, immediately followed by a stop command. There is no ability for easy satellite tracking with the current setup.

Each stepper motor shaft is fitted for shaft encoders. Only the DEC motor retains its encoder PCB. The required diametrically opposed magnets are missing from both output shafts. Documentation of the rotary encoders indicates this subsystem can be quickly repaired and replaced, using a pair of diametrically opposed disc magnets and a replacement AS5134 high speed magnetic rotary encoder. Accuracy and practicality of the system has been questioned in previous work due to the equipment precision of ±18’’ [9].

With this assessment of the telescope mount baseline complete, a plan to develop the system to meet the projects aims was designed. This improvement benchmark included a home position sensor, a method to drive the stepper motors using OnStep and the feasibility of using an IMU on the mount.

C. LX200 Telescope

An examination of the LX200 telescope mount was undertaken to determine the configuration of the equipment at project start. A benchmark to return the system to functional use was designed thereafter. The mount was missing a motor control board, removed after it malfunctioned. A replacement control board had been designed and built, this was provided for the inspection. Reviewing the circuit diagrams and code [16] provided for the replacement control board showed development had started on the replacement in 2013. The new design was centred around an outdated OnStep code and heavily modified to attempt to use the DC motors present on the mount. Testing of the code demonstrated it was incomplete. The hardware setup of the LX200 drives are two DC motors, ALT and AZM. The drives have reduction gearboxes and a worm wheel to produce a total reduction of 10,800:1. Feedback from the motors is by quadrature encoder wheels mounted on the drive shafts. Each encoder wheel has 90 slots for a count of 360 positions per drive shaft rotation. This equates to a count of 3 per 1°. The AZM worm wheel contains a hall effect sensor designed to act as a home position sensor. The sensor is placed to enable a home position accuracy of ~±8” [17].

The intention of the new control board and software is to use speed monitoring and control via the quadrature encoders and the Flexi Timer Module (FTM) onboard a Teensy 3.2 microcontroller using Pulse Width Modulation

Figure 1. Block diagram of roof telescope at project baseline.

Figure 2. 8 Bit data words used to control step rate.
A small, low cost amateur telescope, the telescope mount was modified with a designed and 3d printed azimuthal gear with motor mount and an altitude gear with motor mount. The size of the gears was chosen to fit the mount and the gear pitch of 16 was chosen to allow for rapid prototyping on a 3d printer. The stepper motors chosen were NEMA 17 size and 400 step resolution [20]. This motor was chosen due to its small step size, 0.9°, and small size while offering adequate torque, 48N.cm. A Teensy 3.2 microcontroller and a pair of TMC2130 stepper motor drivers were chosen based on the introductory design at the OnStep site [21,22].

The gear ratio, combined with the step size and micro-stepping of the design determines the smallest micro-step size of the mount, for both ALT and AZM, IAW equations (2) and (3).

\[
\frac{360° \times 60′ \times 60″}{\frac{48 \text{ teeth}}{12 \text{ teeth}} \times 400 \text{ steps} \times 32 \mu \text{steps}} = \frac{1,296,000″}{51,200 \mu \text{steps}} = 25.3125″/\mu \text{step} \tag{2}
\]

\[
\frac{360° \times 60′ \times 60″}{\frac{137 \text{ teeth}}{12 \text{ teeth}} \times 400 \text{ steps} \times 32 \mu \text{steps}} = \frac{1,296,000″}{146,133.33 \mu \text{steps}} = 8.87″/\mu \text{step} \tag{3}
\]
The OnStep code was modified for the unique gear ratio’s and resolution of the telescope mount. Completion of the prototype circuit and testing of the device proved the feasibility of OnStep for use on the larger telescope systems. The system operates under ASCOM drivers used by Sky Planetarium and Stellarium, both common planetarium and satellite tracking software used for research [5,4,6]. The desktop telescope was also used to test iterations of prototype code, before use on the roof telescope system to provide risk mitigation on the larger, more expensive equipment.

B. Roof Telescope

To develop the roof telescope system following the system baseline, the required sub-systems were identified and developed.

1. Dome Automation

The dome housing the telescope system requires manual operation to both open and close the dome roof aperture and dome rotation to the viewing position see Fig. 4. The manual operation of this large metal structure is physically very difficult. For the telescope to provide the best opportunity for use, it should be coupled with an automated dome system for ease of use. Subsystem improvement would allow users to operate the equipment remotely over the internet. Connectivity of this type may also allow for global use of the system through various global share projects similar to the FTN [23].

An investigation was carried out to review alternative automated dome systems available commercially, to determine if a similar solution could be purchased and installed on the existing dome. Investigation into commercially available products, through both professional companies and open source hobbyist pages, showed a common trend on all other dome infrastructure, in opposition to this subsystem, the location of rotating guides and wheels are reversed. The location of wheels and guides on the roof telescope dome are all attached to the dome itself. These roll in contact with a horizontal support ring on the wall of the structure, refer Fig. 5. All other dome and wall systems investigated exhibit these systems attached to the wall or floor of the structure and the dome remains free to rotate [24,25,26]. This design obstacle indicates that commercial and hobbyist solutions cannot easily integrate to the current infrastructure in place due to this interference with the rotating protrusions.

Options investigated to rectify the issue included the replacement of the entire dome. This replacement could either utilise the existing wall or include replacement of the entire structure. A commercial off the shelf (COTS) solution was investigated and priced to provide a range of possible solutions [24]. This solution would provide automation of the subsystem and complies with ASCOM standards by providing an entire system ready solution [6].

A more cost-effective option utilising the existing infrastructure was conducted. Measurements were taken of the dome and wall in several places to determine the roundness of the structure using a dial indicator, see Fig. 6. The dial indicator was placed alternatively on the wall and the dome. The dome run out was measured to be ±2.00mm. These measurements were used to design two possible solutions to the dome training automation. The first, was to heavily modify the dome and wall by first removing...
existing wheels and guides before reattachment to the wall. This would allow for a simple COTS system to be attached to the dome. The second solution, consisted of an attached metal chain above the obstructions, clear of all rotating wheels and guides. This chain could interface to a driving cog or wheel which could be used to rotate the dome. The chain and driver solution would require significant design work for integration to the ASCOM system.

The findings and recommendations for the dome automation solution were completed once the cost and difficulty in these solutions indicated the most benefit would be gained from the commercial solution to replace the dome. This was the preferred choice, however further work on this sub-system is now beyond the scope of this project.

2. Home sensor

The purpose of the home position sensor is to provide a location to calibrate the telescope mount position. The need for the sensor is due to the narrow view angle and difficulty in manual alignment. The requirement for such a device has been identified in past work [9]. The home position sensor was created after reviewing similar proven methods used by other systems [5,17]. The process of ensuring the correct alignment of a telescope mount is to first calibrate the telescope in its home position. This will ensure the controlling software is aware of the mount’s alignment. An easy to locate, bright star, is chosen to complete the alignment by commanding a GOTO. The mount will move approximately to the star, depending on home position and movement accuracy. Ensuring the star is located in the centre of the viewing window, adjusting mount position as required, the telescope mount position can now be synced to this known star location in the astronomy software. This process is often repeated for three alignment stars [17]. A home position sensor must ideally have a calibration accuracy smaller than the view angle of the telescope and camera fitted to the mount. The telescope mount is currently fitted with a Meade 0.4m Cassegrain telescope and an ATIK 414EX Mono camera providing a viewing angle of approximately 15° [27]. The current absence of a home sensor is what made this high precision but narrow field telescope extremely difficult to point and locate, even to the first alignment star, and hence currently unusable. Therefore, the impact of designing this sensor to operate on two axes is highly crucial to the accuracy and useability of the system. The viewing angle was determined by comparing an image of Jupiter and its moons using Stellarium see annex A.

The most common implementation of home position sensors, used in commercial telescope mounts, utilise hall effect sensors for position sensing. OPB706A reflective object sensors were used to provide a similar function in this design [28]. A reflective object sensor consists of an IRLED alongside a phototransistor. The sensor is designed to provide current flow when a reflective object passes within a few millimetres of its field of view. A pair of OPB706A were provided to accomplish this task. After several prototype models were designed and tested the final model was tested and fitted to the telescope mount, Fig. 7. The sensor consists of a 3d printed base, designed to fit to the existing hardware without obstruction and a PCB. The final design of the home position sensor features sensors with adjustable distance and IRLED currents. This ensures the device can be calibrated and maintained in the future. The design includes a removable Teensy 3.2 microcontroller and an interface connector, this enables use for a multiorole configuration, a standalone unit and as a plug-in to the OnStep microcontroller [18]. Two reflecting surfaces, for RA and DEC alignment were also constructed and fitted to the mount.

In standalone mode, power provided through either USB or the interface connector is required for operation. The LED on the teensy 3.2 remains off while either RA or DEC is misaligned. When alignment of RA is achieved, the LED flashes at a slow rate, 250ms on and 750ms off. Upon alignment of the DEC axis, the LED flashes at a fast rate, 250ms on 250ms off. When both axis are aligned the LED remains on. The reflective surfaces fitted to the mount feature a black background with a narrow strip (1mm wide) of white reflecting material. The accuracy achieved from this method is presented in the results section.

Figure 7. Completed home position sensor.
In the OnStep microcontroller plug-in mode, the interface connector provides two output signals, one for RA and one for DEC, to the OnStep microcontroller. The reflective strip consists of a non-reflective half (black) on the RA and DEC minus side and a reflective half (white) on the RA and DEC plus side. When commanded to find the home position on the mount, the edge transition between the two halves is sought. OnStep senses the output from the sensor, high for black, low for white, and commands the mount to move towards the edge. When the transition from high-low or low-high is detected, mount motion is reversed, and the speed is halved. This process is repeated three times until the third transition edge is detected and the mount is stopped. The position is set as home in the planetarium software and the process is complete [5]. The accuracy of this method is presented in the results section.

3. Drive Method

Driving the telescope mount stepper motors was achieved by connecting the D15 connectors on the stepper motors to new stepper motor drivers. These drivers are controlled by an Arduino Mega which hosts the OnStep code [29]. TBB6600 stepper motor drivers were chosen to meet the high current rating of the stepper motors [30]. The drivers can provide 32 micro-step resolution to the mount’s stepper motors. The possible resolution of the mount can be determined from equation (4).

\[ \frac{360° \times 60′ \times 60″}{200: 1 \times 200 \text{ steps} \times 32\mu\text{steps}} = \frac{1,296,000″}{1,280,000\mu\text{steps}} = 1.0125′/\mu\text{step} \]  

This is a significant improvement over past work which utilised 8 micro-step resolution [9]. The maximum slew speed of the telescope was limited to 2.2°/second due to its large size and inertial weight. This was achieved by limiting the micro-step rate to 128μsec between steps. Tests of the mount movement, including GOTO and tracking were completed and are presented in the results section of this report.

C. LX200 Telescope

The benchmark for the LX200 telescope was achieved in three stages. First a method of reading the position and speed of the DC motors. Second, a controller for turning the micro-step output mode of OnStep to DC motor speed and position. Last, an integration of the control system solution with an OnStep driver and microcontroller.

1. Quadrature encoding

To control the speed and position of the telescope mount a Teensy 3.2 microcontroller was selected for the hardware quadrature encoding. A software method of quadrature encoding was first tested resulting in the discovery of a faulty LM339 comparator on the ALT motor encoder. This fault is possibly the cause of the original system failure [31,32]. Hardware quadrature encoding offered an increased response time for the controller over a software quadrature encoding method. This improvement is possible due to the required polling of pins, or interrupts, for the software implementation. The Teensy datasheet was the only source suggesting evidence of utilising the FTM hardware quadrature encoding [18]. A method was created to utilise these hardware features of the chipset. This required use of alternate pinout configurations and FTM register changes. The result of the difficult work proved a faster method of responding to feedback from motor position. The quadrature encoder count, or position, is available on a register. This method removed the chance of missing position changes due to the polling of input pins. The removal of lengthy overhead interrupts resulted in a faster response during the motor control method.

2. Motor Control

To transform the micro-step commands from the OnStep microcontroller a proportional controller was designed. The Teensy 3.2 microcontroller, with the hardware quadrature encoding, accepts the step and direction commands from the OnStep microcontroller for both ALT and AZM. These interrupts increase a target position number for which the quadrature encoder position tries to match. A PWM signal is output from the Teensy to a Duinotech motor controller module [33]. This system creates a basic closed loop controller. Enhancement to the design included the monitoring of the distance between current position and target. Thresholds were designed to
alter the PWM signal, dependent on the target distance, to create a P controller. This controller allows the system to respond to both GOTO and tracking movements as required.

3. OnStep Integration

The method to integrate the mount for use in OnStep involved balancing the required resolution for accurate mount position. This needed to be achieved while limiting the oscillations caused by the controller to seek accurate positioning from the DC motors. Each full rotation of a DC motor is equal to 120°. Using all 360 positions of the quadrature encoder wheel makes the possible mount resolution 1/3°. Each micro-step input was mapped to an encoder count of 3. This resulted in a final resolution of 1°/μstep. Tests of the system responding to step inputs showed no sign of oscillations and little overshoot when approaching target position. The OnStep driver was modified for the resolution of the system and the maximum rate of micro-step commands was set to 256μs, limiting mount slew rates to 1°/s.

The hall effect sensor used for providing home position was not included in the modifications to OnStep and instead was connected to an LED to provide visual indication of home position. This allowed for a manual method of homing the mount.

Tests of the mount movement for GOTO and tracking were unable to record results in time for inclusion of this report.

IV. Results

The desktop telescope is complete and ready for use. Its wide viewing angle and micro-step accuracy make it suitable for observing the location of planets and constellations of interest. The telescope met its required aims as a proof-of-concept by providing a testing platform for OnStep software in an unmodified controller and pointing mode with dead reckoning. The telescope functions as a simple telescope with the enhanced useability to act as an automated GOTO and tracking telescope system.

The roof telescope is complete and tests for functionality and accuracy were undertaken. The test results are presented in three stages. First the home position sensor was tested for accuracy and reliability. Second, the accuracy of the control system to find and track stars using dead reckoning. Third, the motion tests of the IMU. The results of these tests are presented below.

A. Home Position Sensor

The home position sensor was tested for accuracy in both standalone mode and OnStep integration. The test involved micro-stepping the roof telescope across the sensor, in both RA and DEC and recording the voltage from the optical sensors. Three variables were altered during these tests, the distance between sensor and reflecting panel, IRLED currents and types of reflecting surfaces. The results from this test method allow the calibration of the sensor. A sample of results are presented in Fig. 8. In standalone mode the home sensor operates by indicating the home position when the voltage reading is at a minimum. This was set to 0.5V. A narrow minimum voltage, below 0.5V, for a short step range is desirable for this mode.

When integrated with OnStep the most desirable result is when the transition between logic states occurs over the smallest range. These are represented in the results as a steep transition slope. The results for RA are ~20%
less accurate than DEC due to the distance the sensor is placed from the point of rotation. The results of the RA are shown and discussed to represent the minimum achievable accuracy.

These results enable the telescope to home to a position within 3 micro-steps in standalone mode for an accuracy of ±2.025”. The OnStep integration mode will enable the telescope to home within 2 micro-steps for an accuracy of ±1.0125”.

B. Movement and Tracking

The accuracy of the completed system was verified by centring a star in the centre of the telescopes field of view. The system was synchronised to this star location. A series of 5 GOTO movements, away from this location and back are used to determine the reliability of the system to return to the same location. The result of this is presented in Fig. 9.

This result shows the total displacement of the system after a known star, Rigel Kentaurus, was used to synchronise the systems location. The image captured on the ATIK 414EX mono camera is 1391 x 1039 pixels with each pixel equal to ~1” [27]. The centroid of the star was measured in each frame, with the difference used to calculate the mounts movement. This result shows a cumulative inaccuracy of 208” in DEC and 291” in RA.

System tracking accuracy was assessed by synchronising the location to a known star. The ability to accurately track an object over long exposure periods can be determined and corrected for with corrections to the sidereal tracking rate. The image for a 60 second exposure is shown in Fig. 10.

This image shows a drift in the position of stars over the 60 second exposure. During tracking of a star, this GEM will remain stationary in DEC and use sidereal rate to move in RA. This image shows a drift of 192” during the exposure. The downwards direction of the drift indicates the sidereal tracking rate is 3 micro-steps/second too low. The nonuniform brightness and width of the star trails indicate the variation in the telescope position during the exposure. There is little gain in correcting this one instance as it will be a factor of the mount’s balance and hence the pointing direction. More extensive work is required to calibrate the mount, removing such errors from the entire range of motion.
C. IMU

The IMU is attached 160mm from the RA axis and 220mm from the DEC axis. Although attaching the device further from the axis points of moment would improve the resolution, this position offered a convenient mounting bracket previously installed on the system. A series of tests were conducted for the mount including stationary, sidereal tracking and GOTO movements along either RA or DEC axis. These tests were designed to both test the mount movement and the resolution above the inherent noise of the IMU.

The results from the sidereal tracking test are used to examine the feasibility of using the device to detect motion during image capture of long exposures. This use would require mount movement and orientation to be discernible during tracking of objects. Additionally, this test is used to look for unwanted mount motion. The result of this test is shown in Fig. 11. The test recorded the mount motion, sampling at 100Hz over 6 seconds during sidereal tracking of the star Artemis. The mount micro-stepped 6 times during this window. Of the 9 possible measurements, the Z axis of the accelerometer is displayed here. The location, orientation and sensitivity of the mount and IMU placed this reading in the best position to detect mount motion. The result of the test shows no discernible acceleration above the IMU noise level for a stationary test with the same start position. This indicates a level of smoothness of mount motion during the test.

The results from the RA and DEC GOTO tests are used to assess the mount movement and the IMU ability to perform as an actuator. This requires mount movement and orientation to be discernible to enable use as a feedback system. The result of the test is shown in Fig. 12. The test involved commanding the mount to move along a single axis, either the RA or DEC. Mount motion is again recorded with a sampling rate of 100Hz for a 6 second window.

![Figure 11. Mount motion test during stationary and star tracking.](image1)

![Figure 12. Mount motion test during isolating RA and DEC movement at maximum slew rate.](image2)

The maximum rate of the telescope is restricted to 2.2°/sec. The test result encompasses a movement of 13.2° during the 6 second exposure. During this movement the motors were driven through 1465 steps (46,875 micro-steps). There is a clear change of the gravity vector during these movements which can be used to track the mount orientation. Under this low sampling rate, compared to the mount micro-step frequency of 7.8 kHz, there is no clear indication of motion due to either step or micro-step variations. There is, however, noticeable fluctuation in the mount motion.

V. Conclusions

The project aim of providing enhancement to the automation and functionality of the telescope mount equipment was achieved. Tests of the roof telescope system proved the ability of the system to locate and track objects using current planetarium software. This was achieved through the design, construction and installation of a home position sensor, a drive control solution and an OnStep driver integration. This has provided functions...
and accuracy beyond what was previously available on the system. Tests of the mount motion using both image capture and visual inspection combined with results from the IMU support the objectives of the project. The system is easy and accurate to use, meeting the needs for research work and future use. OnStep was successfully integrated into all three telescope systems using a combination of stepper and DC motors. Microcontrollers were utilised to provide open loop control solutions through dead reckoning with stepper motors. A closed loop solution utilising DC motors and quadrature encoding was also completed. Although testing of the LX200 was not completed, preliminary movements of the mount suggest that a more robust PID controller may need to be incorporated due to the significant inertia of the mount hardware over the simple control method designed.

VI. Recommendations

A. Roof Telescope

The original stepper motor controller for the roof telescope featured a unique step rate controller. This device can provide motion, smoother than that of the TBB6600 used in this project due to the 1024 micro-step resolution over the 32 micro-steps. Future work on the telescope could improve the mount motion. Combining this with Periodic Error Correction (PEC) could further remove most of the tracking inaccuracy shown in the results. Further to this improvement, much of the research work planned for future use at UNSW involves tracking of LEO satellites. Confirmation of the ability, or limitations of the system to track such objects would be of benefit to characterising the system.

B. IMU

The examination of the IMU in this report was centred on an examination of the possible uses such a device could provide to telescope motion tracking. The results suggest the ability for the device to measure mount motion during the tracking of a LEO satellite, with rates approaching the maximum speed currently set by the roof telescope mount. This feedback may be useful in predicting or correcting mount motion during these activities.

C. LX200 Telescope

The LX200 was not completed in time to provide any results to characterise its performance. The motor control method provided adequate results when testing the drive units removed from the inertial load of the mount and attached telescope. The system could be improved, and its performance characterised, with the design of a PID controller. Tests of the system could be undertaken alongside another, original LX200 to determine the effectiveness of the design solution. This would assist to evaluate the potential use for the system.

VII. References


Final Project Report 2018, UNSW Canberra at ADFA
[16] A. Lambert (5 May 2017) AJLMeadeController, ADFA.
[34] F. Gasdia (May 2016). Optical Tracking and Spectral characterization of CubeSats for Operational Missions. Embrey-Riddle Aeronautical University.
[37] TTElectronics Datasheet (Issue D October 2016), Reflective Object Sensor OPB706A.

VIII. Appendices

Appendix A. Photograph used for confirming Viewing Angle.
Appendix A - Photograph used for confirming Viewing Angle,

Image by ASLT Clinton Kerr, captured by roof telescope 748pm 28/09/2018. ATIK 414EX monochrome camera, 1 second exposure 15° view angle. From Top Left Ganymede, Jupiter, Io and Europa.