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Argus Optical Array motion control: novel pointing and tracking solutions for large array telescopes

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ABSTRACT

The Argus Optical Array is an all-sky telescope composed of 900 0.2-m off-the-shelf, wide-field telescopes that covers 20% of the entire sky in each exposure. Using low-noise CMOS detectors, the array reaches g=19.6 in minute-long exposures, while deep coadds will reach g=23.6 every five nights. By observing the entire accessible sky simultaneously, Argus is sensitive to timescales orders of magnitude faster than most time-domain surveys, whose cadence is fixed by the time between visits to the same field. All 900 telescopes are mounted on a single platform that rotates about an axle; thus, operating a complex array telescope is reduced to smoothly tracking using this one axle. This requires few-arcminutes pointing of the system's rotation axis, as it is impossible to make a conventional pointing model for an all-sky telescope. The Argus polar alignment system, first demonstrated on the 8-ft-diameter Argus Array Technology Demonstrator, consists of custom software that controls two off-the-shelf high-load-capacity linear actuators attached to one end of the pointing axle of the Argus Optical Array. The Argus tracking system is a closed feedback loop that consists of an encoder and custom linear actuator, which leverages the large lever arm of the system to easily rotate our telescope platform. This approach was tested on the Argus Array Technology Demonstrator. Here we detail both motion control systems, our automated polar alignment routine, and performance on polar alignment and tracked image quality.

Keywords: Survey telescopes, array telescopes, precision motion control, astronomical instrumentation

1. INTRODUCTION

Currently, most searches for fast-evolving transient phenomena are executed by subdividing the sky into equal-area fields observed in deep drills. This approach has been successful but is necessarily limited to relatively common transients that can be found in narrow fields of view.[1,2] Another approach to reaching fast transient phenomena is to survey the entire sky using ultra-wide field of view (FoV) telescopes; this approach trades depth and resolution to gain rapid all-sky monitoring capabilities. The Evryscopes take this approach with a north/south pair of all-sky telescopes. Each is made of twenty-seven 61mm wide-field telescopes, all on a standard German equatorial mount. The Evryscopes collectively monitor $16,512$ sq. deg. down to g'=16, with 13.1 arcseconds per pixel sampling, at a 2-minute cadence.[3,4] The Evryscopes have undertaken surveys searching for long-term variability,[5–7] in addition to detecting fast transient events such as flares from cool stars[8–12] and a fog of Earth-orbiting satellite glints that all ultra-wide-FoV surveys will need to discriminate from real transient astrophysical phenomena.[13]

The Evryscopes demonstrated that a moderate-resolution, all-sky telescope made of commercially available off-the-shelf components is feasible. Recently, advances in CMOS technology have enabled new surveys capable of second-timescale cadences, such as the Organized Autotelescopes for Serendipitous Events Survey,[14] the Tomo-e Gozen instrument on the Kiso Schmidt telescope,[15,16] and the Weizmann Fast Astronomical Survey Telescope.[17] The Argus Optical Array is an upcoming all-sky system that builds upon the monolithic array telescope concept from the Evryscope and leverages new high-speed sensors to survey the sky at arcsecond resolution.

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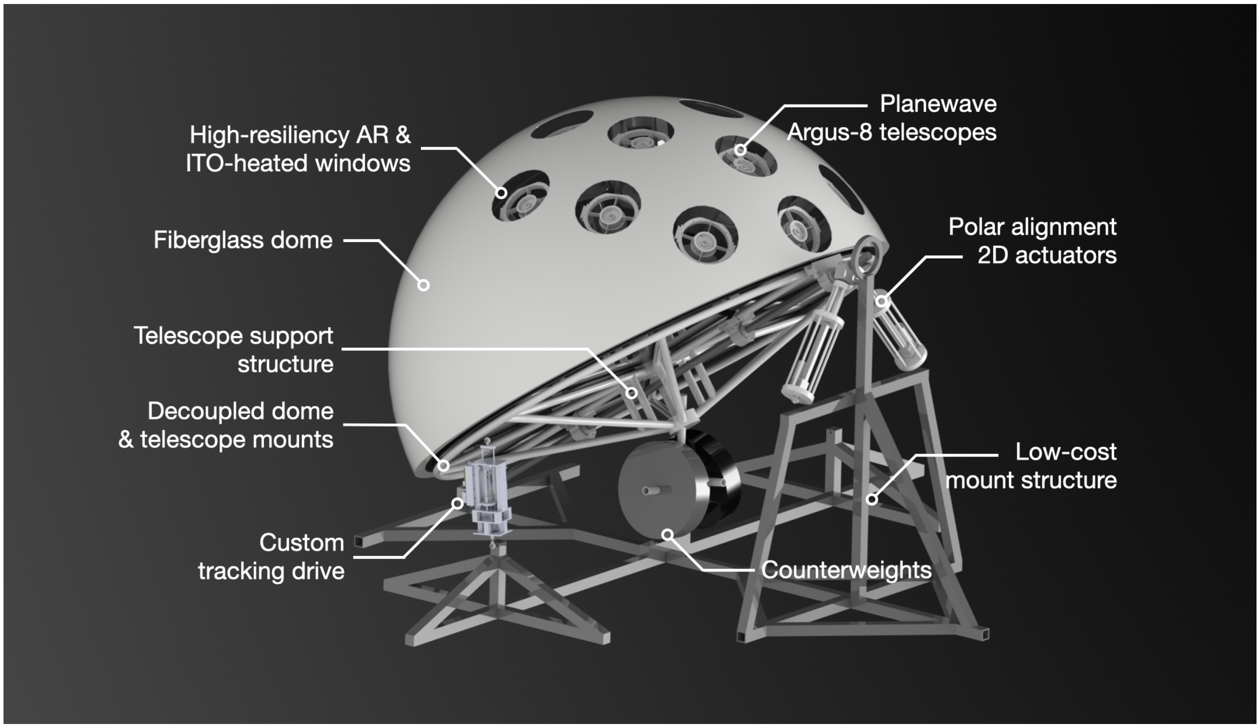

Figure 1. A concept rendering of the A2TD and showing our custom off-axis tracking drive and polar alignment system. The 8-foot dome and telescope platform rest on a common rotation axis but are vibrationally isolated.

1.1 The Argus Optical Array & Argus Array Technology Demonstrator

The Argus Optical Array will be a wide FoV array of 900 off-the-shelf, 0.2-m telescopes. Using low-noise CMOS detectors, Argus will reach g=19.6 in minute exposures, while deep coadds will reach g=23.6 every five nights.[18] Every Argus exposure will cover 20% of the entire sky by mounting all telescopes on a common platform that rotates about an axle, where the pointing of each telescope is carefully predetermined. This monolithic design greatly reduces the number of moving parts and the baseline maintenance requirements associated with array telescopes. Furthermore, by maintaining all individual telescopes inside a sealed and thermally controlled environment, we will maintain consistent optical performance over long periods of time. In preparation for the full array, we have built two precursor systems – the Argus Array Technology Demonstrator (A2TD) and Argus Pathfinder, the mid-scale prototype for the Argus Optical Array. It is entirely inside a temperature-controlled enclosure, so temperature effects do not need to be modelled. Pathfinder is a 38-telescope system that monitors all declinations from -20° to $+72^{\circ}$ simultaneously and will be the first extremely-high-cadence wide-field survey covering the whole sky each night. Argus Pathfinder will leverage all motion control and pipeline developments from the Argus Array Technology Demonstrator and is planned for on-sky operation at the Pisgah Astronomical Research Institute (PARI) in Q3 of 2022.

The A2TD is a 9-telescope test bed used to prototype the Argus motion control technologies, thermal control design, and early pipeline development. A concept rendering of A2TD is shown in Figure 1 with all of its major components. The mount for the telescope platform and dome is called the "Hercules mount", a structure made of steel tubing that provides anchor points for the rotation axis of the A2TD, mounting arms for the tracking drives, and slots for the polar alignment system. The pair of tracking drives mounted off-axis at the edge of the telescope platform allows us to take advantage of the large lever arm for smooth sidereal tracking. The polar alignment system, a pair of low-resolution linear actuators, attaches to the top of the A2TD rotation axis so we can automatically polar align this system to Earth's rotation axis.

The dynamic structure of the A2TD is an 8-foot diameter subsystem that consists of two vibrationally disjoint structures, a telescope platform that holds all 12 telescopes at a predetermined pointing and an 8-foot diameter dome that isolates our telescope array from weather and provides a thermally stable environment. The stability and portable design aspects of the Hercules mount allowed us to rapidly prototype our motion control systems and retire other technical risks associated with building a 50-foot-scale array telescope. For detailed information on the design and operation of A2TD, we refer the reader to *The Argus Array Technology Demonstrator: Rapid prototyping of core technologies for an all-sky multiplexed survey telescope (Corbett 2022)* and *The Hercules Mount: Shouldering the Weight of the Argus Optical Array (Gonzalez 2022)*. In Section 2 we present the A2TD tracking drive and its performance. We describe the A2TD polar alignment system with performance measurements in Section 3 and detail design improvements in the motion control systems for the soon-to-be deployed Argus Pathfinder in Section 4.

2. TRACKING DRIVE

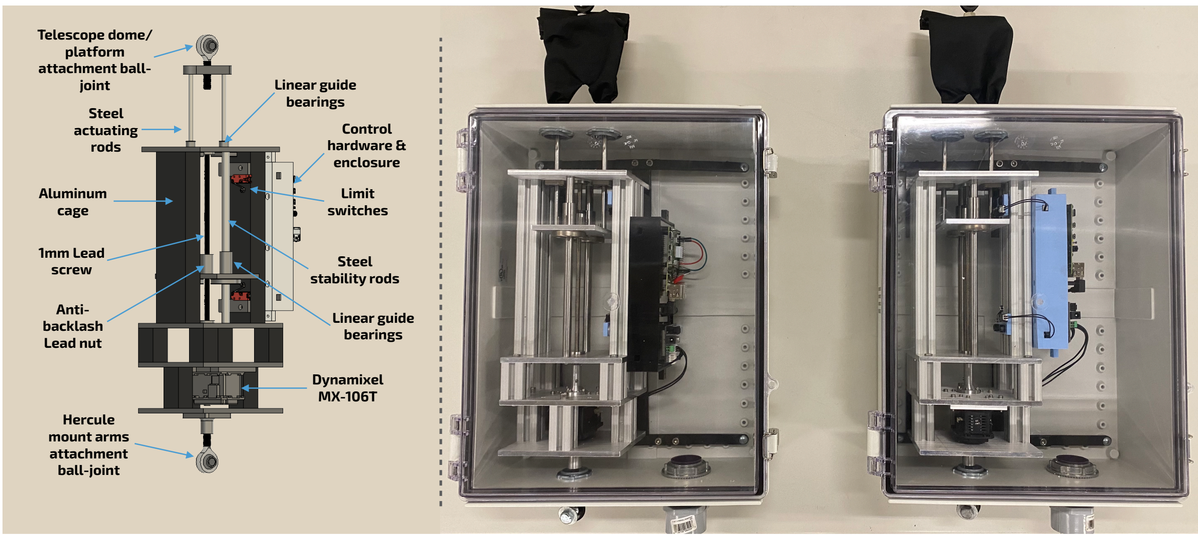

Figure 2. A conceptual overview and production versions of the two tracking drives we designed and built for the A2TD. Both tracking drives and associated control hardware are enclosed in a waterproof composite housing, allowing them to be deployed in outdoor environments with minimal maintenance.

We require the A2TD telescope platform to precisely track the sky at the sidereal rate; the performance of this tracking sets the image quality for all of the telescopes in the array. Below are the requirements we considered for the tracking drive design:

1. Sidereal tracking at a rate of 15 arcseconds / second.
2. The tracking drive shall allow for 5 degrees of tracking range.
3. The control system shall be a closed feedback look for active position control.
4. There shall be fault tolerance via limit switches and self recovery routines.
5. The control system will be an asynchronous HTTP web server for automated control via the Argus Array control system, all accessible from the system's internal network.

The rotation of the telescope platform and the dome is decoupled to minimize tracking noise from the outside environment. Thus we require a total of two tracking drives for the A2TD. The dome tracking drive does not have to rotate its component at the same level of precision as the telescope platform; however, we can implement a simpler and more robust control system by making two identical linear actuators capable of few-micron-scale motions. Here we present the mechanical design, control hardware and system, and performance of the A2TD tracking drive.

2.1 Mechanical Design

The A2TD tracking drive is fundamentally a lead screw linear actuator we communicate with over an HTTP web server. In order to achieve the precision required for sidereal tracking, we require the combination of a small pitch lead screw and a servo motor with a built-in high-resolution encoder. For the scale of A2TD, we chose a 1mm lead screw and a servo motor with a built-in encoder with $4,096$ pulses / revolution. This motor and lead screw combination makes sidereal tracking possible while placing the tracking drive at the edge of the telescope platform and dome. We reduced mechanical systematics that would propagate into our science images by using a spring-loaded lead nut to minimize backlash. The lead screw is then fixed at both ends inside the linear actuator assembly via a pair of custom washers and low-profile needle-roller thrust bearings.

We used a Dynamixel MX-106T high-resolution servo motor to power the A2TD tracking drive. The body of the lead screw assembly is made of off-the-shelf t-slot extrusion, commonly known as 80/20, and 6061 aluminum plate. We also designed a custom rigid shaft coupling to mate our servo's horn to the lead screw. We used 1060 carbon steel linear guide rods to ensure smooth and straight actuations while tracking. For mechanical safety, we placed Omron SPST D3M-01K2-3 limit switches at either end of the linear actuator's range of travel and implemented logical motor shutdowns in our control system when a limit switch is triggered to mitigate critical failures.

The linear actuator assembly, including its control hardware, is enclosed in a Polycase WQ-73 with NEMA 4X / IP67 ratings. We designed custom 3D printed mounting brackets to place the linear actuator inside the Polycase. Both tracking drives connect to their respective structures and anchor points using high-load-capacity ball joints. We required ball joints as the connecting points due to the multiple rotational degrees of freedom required to actuate our tracking drives smoothly.

The last major component of the ATD tracking drive is its high-resolution, absolute position, partial arc rotary encoder, the RESOLUTE BiSS 50nm 26-bit RTLA. This encoder is capable of sub-arc second metrology over the length of our ratchets. This absolute position rotary encoder allowed us to create a closed feedback loop between motor speed and tracking speed and thus enables a combination of PID control and forward modeling of pre-measured periodic errors to achieve sidereal tracking. This encoder is highly sensitive to pitch, roll, and yaw misalignments between it and the scale it reads. The tight tolerances specified in the user manual can seem intimidating; however, we found quick success in mounting the encoder and scale to the A2TD by using a custom 3D printed bracket for the scale and a multi-axis articulating camera arm for the readhead.

2.2 Control System

The ATD tracking drive hardware is controlled using a Raspberry Pi4 model B (RPi4). This edge device manages the MX-106T, the Renishaw encoder, and interfaces with the A2TD observatory control. Commanding our tracking drive is done over an asynchronous HTTP web server implemented using FastAPI. We also implemented a command line client for debugging and use during maintenance cycles. We wrote custom python drivers for the MX-106T.

The result is a lead screw linear actuator capable of few-micron-scale motions that runs as a python based state machine and communicates with the observatory control system. It supports all required motion control for science operations while providing appropriate feedback to the observatory control system.

2.3 Performance

In Figure 3 we present tracking data over seven ratchets performed in our lab environment. We created a closed feedback loop using the Renishaw encoder, which allowed us to leverage a PID controller to maintain optimal tracking performance throughout each ratchet. We achieved the performance shown in Figure 3 by tuning the PID constants to the following values: $K_P = 0.75$, $K_I = 0.1$, and $K_D = 0.5$.

In addition to the tuned PID constants above, we set the PID sample time, or the time before a new PID response is calculated, to $4Hz$. Finally, the control loop samples the rotary encoder at 1kHz. We found that manually tuning the PID constants, starting with the proportional term followed by the derivative and integral constants, allowed us to tune the drive to acceptable performance quickly. With the tuning parameters described

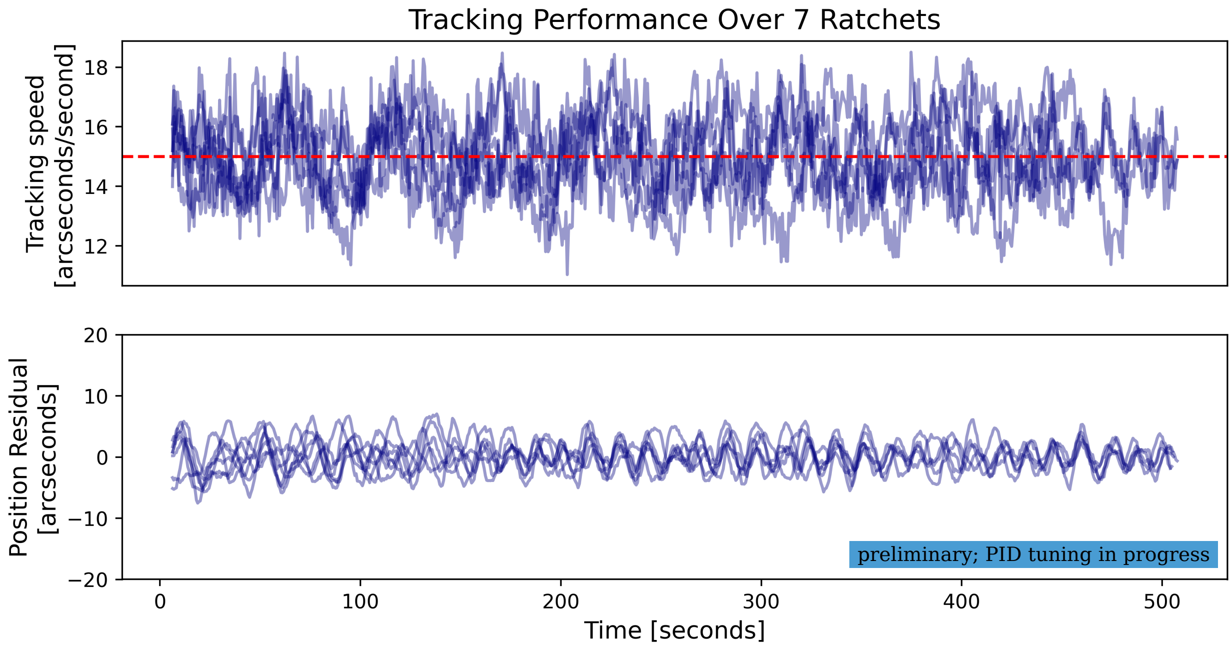

Figure 3. Tracking data measured over seven consecutive ratchets. The sidereal rate is marked as a red dashed line. When applied to A2TD, the current position residuals could imply an increase in our PSFs by almost a factor of two. Argus Pathfinder, however, has a much longer tracking lever arm, and this performance is within-spec for Pathfinder. Performance is being further improved by implementing a two-stage tuning process: PID control and forward modeling of the residuals over many ratchets to predict and minimize their effect.

above, we have achieved tracking performance at a stable rate within 0.016% of the sidereal rate of 15 ”/sec with 1σ speed RMS of 1.26 ”/sec.

This performance shows we will be able to meet Argus Pathfinder tracking requirements, given Pathfinder's much longer tracking-drive lever arm, and we will also add a second stage of motor control, in addition to the PID controller. This second stage will take a large set of ratchet data and model the residuals shown in Figure 2 to predict and further minimize them. This is currently in development.

3. POLAR ALIGNMENT DRIVE

The top-level polar alignment system requirements are:

1. The rotation axis of the A2TD shall allow software-controlled adjustment of its pointing of ±5 degrees in azimuth and elevation.
2. The linear actuators shall allow pointing of the rotation axis within a few arcminutes of Earth's rotation axis. This results in a maximum drift of 10 pixels over a single ratchet.
3. The polar alignment system shall maintain the pointing of the A2TD rotation axis over long periods of time, such that polar realignment is required at most once every few months (depending on ground stability).
4. The control system will be an asynchronous HTTP web server for automated control via the Argus Array control system and for manual maintenance operations, all accessible from the system's internal network.

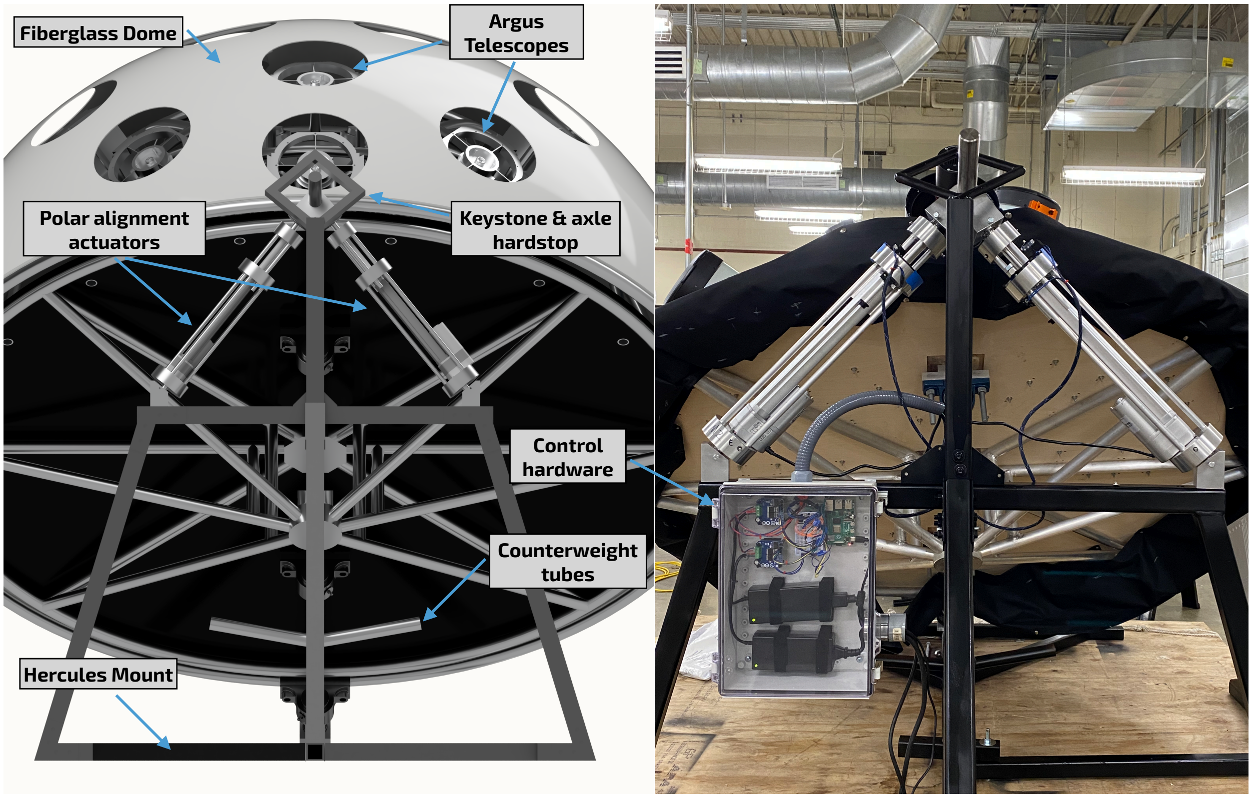

Figure 4. A concept render and production version of our custom polar alignment drive installed onto A2TD with all associated control hardware being enclosed in a weatherproof box.

3.1 Mechanical Design

The mechanical design of the ATD polar alignment drive consists of 3 components and the control hardware. The polar drive is a pair of high-load-capacity optical feedback linear actuators with a 24-inch stroke length.

The remaining components are the linear actuator cages, which provide additional rigidity and connect the actuators to the A2TD Hercules mount, its rotation axis, and the A2TD grip. The grip is a smoothed rectangular pyramid with spherical bearings pressed into the linear actuator connection point (Figure 4). The grip has a set screw to maintain the polar drive at a fixed point on A2TD's rotation axis. Connecting the polar drive to the A2TD via this grip means that commanded positions in either azimuth or altitude require movements from both actuators.

3.2 Control System

The A2TD polar drive hardware is controlled using the same type of edge device as the tracking drive, a RPi4. The control hardware is shown in a waterproof Polycase in Figure 4. We used the same control framework as the tracking drive, enabling automated polar alignment. The RPi4 is responsible for commands from the observatory control and, from there, engaging the Firgelli Automations linear actuators by commanding a pair of high-power motor drivers. We produced a custom software stack to provide motor calibration, motion control, polar alignment capabilities (Section 3.2.1), and fault tolerance.

3.2.1 Brute-Force Polar Alignment Method

To polar align the A2TD, we must align its rotation axis with the Earth's. We must find where the rotation axis of the system is, in local sky coordinates, so we can use the polar drive to accurately repoint it as needed. Our method uses the polar telescope on the A2TD to search for its rotation axis, which is assumed to be in this telescope's FoV. We follow these steps to polar align the A2TD:

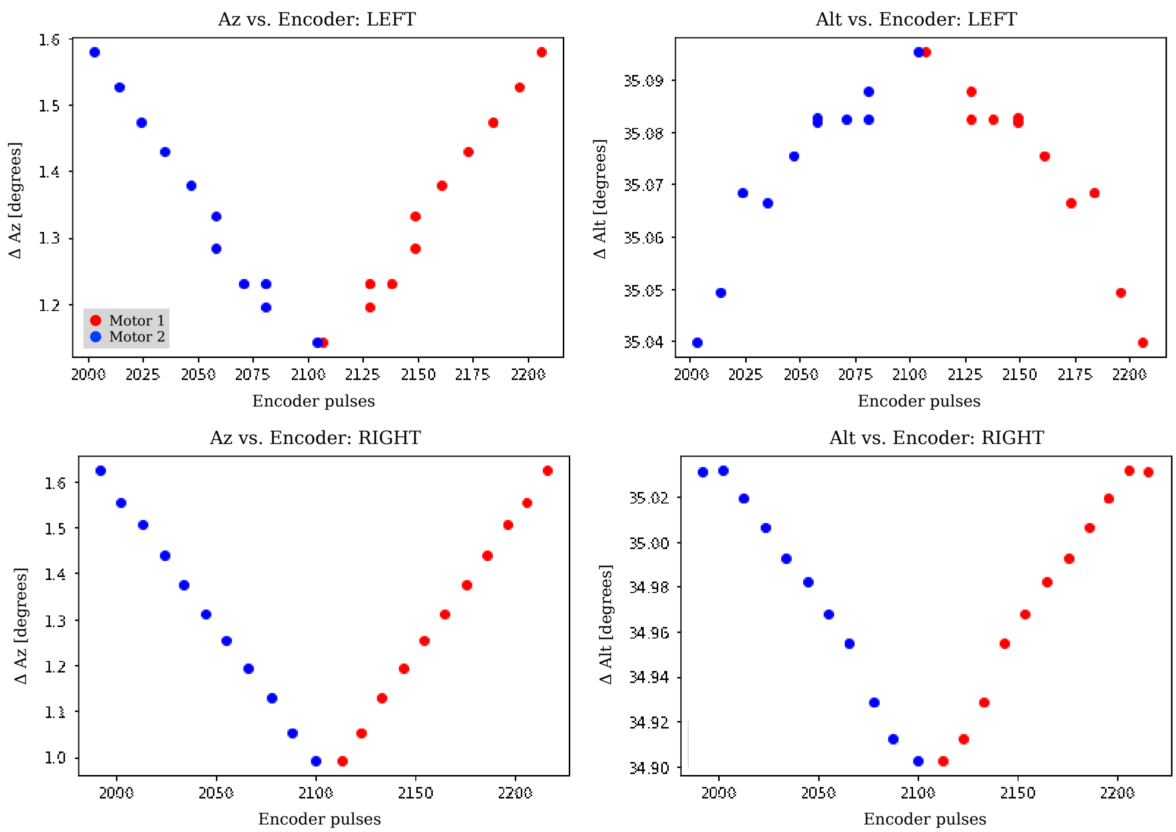

Figure 5. Calibration data that maps encoder pulses from the polar drive to change in coordinates of the A2TD rotation axis in the local horizontal coordinate system

1. Take a pair of images at different hour angles.
2. Convert the image coordinates to the local horizontal coordinate system.
3. Measure the amplitude of the change in coordinates for each corresponding pixel between the two images.
4. Find the minimum of the field created in (3) using a blind walk, this is the rotation axis of the A2TD.
5. Measure (ΔAzimuth, ΔAltitude) between the rotation axis and the ICRS pole.
6. Use the polar drive to apply the offset in (5).

3.3 Performance

The A2TD polar drive's performance ceiling is defined by the encoder to sky motion calibration and by the resolution of the encoders built into the linear actuators.

The calibration during commissioning is a slow process that commands both linear actuators over their entire range of travel. First, we measure the total number of encoder pulses associated with the full throw of each actuator, and we do this multiple times to calculate an average. Next, at each discrete increment, starting at the lowest possible position, we take 1-second exposures and record the center coordinates of each image associated with the current encoder counts on each motor. During the commissioning of the A2TD, we used a total of 10 realizations for each of the four moves associated with the polar drive: up, down, left, and right (Figure 5). We used these data to create a linear map of encoder pulses to sky positioning of the A2TD's rotation axis. We note that given the pulse counting accuracy on the linear actuators of +/- 5 pulses, the intrinsic noise floor on positioning accuracy given the length of our rotation axis and the calibration procedure is 3.7 arcminutes.

Early polar alignment results completed in Chapel Hill, North Carolina show polar alignment accuracy to 10 arcminutes of Earth's rotation axis. This is due to the low-resolution encoders of the linear actuators and how they attach to A2TD's rotation axis. We can repeatably align the A2TD to this accuracy, thus showing that this method of polar alignment is valid for monolithic array telescopes.

4. DESIGNING FOR ARGUS PATHFINDER

The Argus Array Technology Demonstrator is the early prototype of the Argus Optical Array and precursor to Argus Pathfinder. This mid-scale Argus prototype will execute a full sky survey, reaching the entire sky each night down to a limiting magnitude of $g' = 19$ over minute exposures. We developed new tracking and polar alignment technologies for the A2TD that are designed to scale to Argus Pathfinder and, eventually, the Argus Optical Array. This work represents the basis of motion control systems for next-generation monolithic array telescopes. Below we detail a few insights learned during the A2TD development process that we will apply during Argus Pathfinder design and commissioning.

First, we address the tracking drive. This subsystem has demonstrated nearly acceptable performance on the A2TD. We plan to reuse one of the two drives for the Argus Pathfinder tracking drive. The combination of this tracking drive and the encoder that produces a closed feedback loop is ideal for maintaining sidereal tracking with the mechanism at the edge of the telescope platform. The larger lever arm (Figure 3) will allow us to meet the tracking precision requirements for Argus Pathfinder.

The polar alignment drive will see multiple design changes for increased accuracy since current performance from A2TD is a factor of 2.7 larger than our original requirement. With mechanical changes to the polar alignment drive listed below, we expect to reach our nominal requirement of 3.7 arcminutes polar alignment for our mid-scale prototype Argus Pathfinder.

1. Change to a Dynamixel-driven lead screw design for azimuth and elevation. This motor, with 4096 encoder pulses per turn, has been characterized on the A2TD tracking drive and will yield an order of magnitude increase in positioning accuracy.
2. Decouple azimuth and elevation positioning by redesigning the 'grip' to be a trolley system that connects to the back of the Argus Pathfinder virtual polar axis.[19]
3. Increase the number of samples during initial polar drive calibration.
4. Implement a more accurate rotation axis finder that takes into account Earth precession and nutation.

5. SUMMARY

The Argus Optical Array is an all-sky telescope composed of 900, 0.2m off-the-shelf, wide-field telescopes placed on a large equatorial mount. With one structure containing all telescopes, we cannot make a pointing model and therefore require arcsecond-level precision on polar alignment and tracking. The Argus polar alignment system consists of two linear actuators that point the rotation axis of the Argus Optical Array. The Argus tracking system is made of a custom linear actuator and 22-bit rotary encoder, which leverages the resulting large lever arm of the system to easily rotate our telescope platform. By designing and building the A2TD, we demonstrated the scalability of our motion control systems which means we can directly reuse the same tracking drive from the A2TD to follow the motion of the sky with our upcoming mid-scale prototype. Lessons learned from designing the A2TD polar alignment drive have driven design alterations to ensure Argus Pathfinder meets its operational specifications.

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