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CHARACTERIZATION OF DO-IT-YOURSELF (DIY) ULTRA-COMPACT ITERA ROBOTIC TELESCOPE (UTOPIA-SCOPE) MOUNTING

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Abstract

Low-cost and locally fabricated robotic telescope systems are increasingly important for education, amateur astronomy, and basic scientific observation. This paper presents the characterization of the UTOPIA-Scope, a do-it-yourself (DIY) alt-azimuth robotic telescope mount developed using extruded aluminum structures and 3D-printed strain-wave gears. The performance of the mount was evaluated through pointing and tracking tests using an alt-azimuth grid and selected equatorial stars. Image center coordinates were obtained using plate-solving techniques and analyzed with descriptive statistical methods. The results show average pointing errors of 1.600° ± 0.123° in azimuth, 0.415° ± 0.048° in altitude, and 0.451° ± 0.106° in equatorial pointing, corresponding to approximately 96′, 25′, and 27′, respectively. Tracking tests indicate drift rates of 22–36 arcsec per minute, depending on the observed sky region. These results provide a quantitative baseline for the performance of the UTOPIA-Scope mount and serve as a reference for further mechanical and control-system improvements toward future scientific applications.

Keywords: *3D printer, DIY telescope, Instrument characterization, Robotic telescope, UTOPIA-Scope.*

1. Introduction

The use of telescopes has expanded widely, not only in professional astronomical research but also in education and amateur astronomy. This growing interest has led to an increased demand for telescope systems that are affordable, adaptable, and easy to maintain. Recent advances in digital fabrication, particularly 3D printing, have enabled the production of mechanical and optical components at relatively low cost. As a result, do-it-yourself (DIY) telescope systems have become an attractive option for institutions and individuals with limited resources (Quesada, Domínguez, Martinell, Ruiz, & Fernández, 2022) (Roulet, et al., 2018)

In late 2022, the ITERA Lampung Astronomical Observatory (OAIL) developed an altitude-azimuth (alt-az) robotic telescope mount as part of the Ultra Compact ITERA Robotic Telescope (UTOPIA-Scope) project. The mount was designed to be compact, portable, and locally fabricable. Its main structure consists of extruded aluminum profiles and aluminum plates, while its drive system uses 3D-printed strain-wave gears, also known as harmonic drives. Strain-wave gears are commonly used in robotic systems because of their compact size, high gear reduction, and near-zero backlash by design, although small residual errors can still occur in practical applications (Lynch, Marchuk, & Elwin, 2016).

Many DIY and open-source telescope mounts have been developed in recent years, supported by community-driven projects such as the OnStep control system. OnStep is an open-source computerized Go-To firmware for stepper-motor-driven mounts and can be applied to both equatorial and alt-az configurations (Wiki Onstep). These developments demonstrate that robotic telescope systems can be built using accessible hardware and open-source software, making them suitable for educational and small-scale observatory use. At a broader level, the evolution of robotic telescopes has led to the concept of Robotic Autonomous Observatories (RAOs), which are designed to perform observations automatically and remotely while adapting to changing environmental conditions (Castro-Tirado, 2010) (Dimple, S, Omar, & Misra, 2023).

Despite these developments, many DIY telescope mounts are introduced without detailed and published performance evaluations. In particular, quantitative information on pointing accuracy and tracking behavior is often limited or unavailable. This lack of characterization makes it difficult to assess whether such systems are suitable for specific observational tasks or to compare their performance with other mounts.

This study addresses this gap by presenting a performance characterization of the UTOPIA-Scope alt-az mount. The main objectives of this work are to evaluate the pointing accuracy in both alt-az and equatorial coordinate systems, to measure tracking drift in different sky regions, and to provide a quantitative baseline for future improvements. By documenting the performance of a locally developed and low-cost robotic mount, this work aims to support further development of accessible astronomical instrumentation for education and basic scientific observation.

2. Methods

This study was conducted from March to July 2023 at the ITERA Lampung Astronomical Observatory, located on the rooftop of Building C, Institut Teknologi Sumatera (ITERA) (5°21′46.8″ S, 105°18′43.2″ E). The methodology was designed to evaluate the pointing accuracy and tracking performance of the UTOPIA-Scope alt-az mount through direct observational tests. All tests were performed under typical nighttime conditions without active guiding. Time is reported in Western Indonesian Time (WIB). The overall procedure includes the experimental setup, data acquisition, data processing, and performance evaluation using descriptive statistical methods.

2.1. Hardware and Software Configuration

The UTOPIA-Scope mount is constructed using extruded aluminum profiles (20 × 20 mm) and 3 mm aluminum plates as the main structural components. The drive system employs 3D-printed strain-wave gears fabricated from PETG and PLA+, following an open-source design by YMT Lab (Thingiverse.com). PLA+ is used specifically for the flex-spline component to provide sufficient elasticity.

Each axis is driven by a NEMA 17 stepper motor with a resolution of 200 steps per revolution, controlled by an LV8729 driver configured with 1/128 microstepping. The motion is transmitted through a pulley system with a ratio of 80:120, combined with a 39:1 strain-wave gear, resulting in an effective total gear ratio of 58.5:1. During the tests, the optical tube assembly and imaging accessories had a combined mass of approximately 1 kg, which served as a practical reference payload for this study. Table 2-1 shows the specifications of the optical elements at the time of data collection.

Data acquisition and telescope control were automated using the Nighttime Imaging ‘N’ Astronomy (N.I.N.A) software. Plate solving was performed using the Astrometric Stacking Program (ASTAP), while coordinate transformations and data analysis were carried out using the Astropy library in Python (Berg) (Han) (Price-Whelan, et al., 2022).

Table 2-1: Optical Elements Specifications

Component	Specification
Optical Tube	SV Bony SV106 Diameter 60mm Focal Length 240mm Focal Ratio f/4
Camera	ZWO ASI 178 MM Sensor: 1/1,8" CMOS IMX178 Resolution: 6.4 megapixels 3096 x 2080 Pixel Size: 2,4μm Sensor Size: 7,4mm x 5mm Diagonal: 8.92mm Exposure Time Range: 32μs - 1000s

2.2 Pointing Test Procedure

Pointing accuracy was evaluated using two different coordinate systems: the alt-az system and the equatorial system.

For the alt-az test, the mount was commanded to point toward a grid of target coordinates covering azimuth angles from 0° to 360° with 15° intervals and altitude angles from 30° to 80° with 10° intervals. For each target coordinate, the mount was instructed to move to the specified position, capture an image, return to the home position (Az = 0°, Alt = 0°), and repeat the process three times. This procedure resulted in a total of 432 images.

For the equatorial pointing test, five bright stars representing different regions of the sky (northern sky, southern sky, around the zenith, eastern horizon near the celestial equator, and western horizon near the celestial equator) were selected as targets. Each star was observed three times using the same pointing and image acquisition procedure as in the alt-az test, producing a total of 15 images. Table 2-2 shows the target stars used for pointing in the equatorial coordinate system.

Table 2-2: Equatorial Coordinate System Pointing Targets

Object	Sky Direction	Time of Acquisition (WIB)	RA on date (°)	DEC on date (°)	RA on date (h:m:s)	DEC on date (d:m:s)
α Centauri	Southern Sky	10/05/2023 22.01	219.864	-60.831	14h41m13.7s	-60°55'57.4"
α Hydrae	Western Horizon Near the Celestial Equator	10/05/2023 22.16	141.977	-8.700	09h28m43.4s	-08°45'39.6"
α Virginis	Around Zenith	10/05/2023 21.55	201.307	-11.161	13h26m26.0s	-11°17'03.1"
δ Ophiuchi	Eastern Horizon Near the Celestial Equator	10/05/2023 22.11	243.590	-3.695	16h15m34.9s	-03°45'19.9"
η Ursae Majoris	Northern Sky	10/05/2023 22.05	206.890	49.313	13h48m29.4s	49°11'53.1"

2.3 Tracking Test Procedure

Tracking performance was evaluated by continuously following selected stars without guiding. Three stars were chosen to represent different sky regions: Beta Librae (near the celestial equator), Tau Herculis (northern sky), and Alpha Centauri (southern sky). After centering the target star in the image frame, the mount tracked the star from an altitude of 30° until it reached its upper culmination.

During tracking, images were captured at regular intervals of five minutes. This resulted in 37 frames for Beta Librae, 21 frames for Tau Herculis, and 12 frames for Alpha Centauri. These time-series data were used to analyze tracking drift over time. Table 2-3 shows the target stars used for the tracking test.

Table 2-3: Target Stars for Tracking Test

Object	Sky Direction	Time of Acquisition (WIB)	RA on date (°)	DEC on date (°)	RA on date (h:m:s)	DEC on date (d:m:s)
α Centauri	Southern Sky	10/05/2023 22:30	219.864	-60.831	14h41m13.7s	-60°55’57.4”
τ Herculis	Northern Sky	10/05/2023 23:36	245.117	46.255	16h20m28.3s	46°15’19.2”
β Librae	Near the Celestial Equator	12/05/2023 20:43	229.569	-9.469	15h18m16.6s	-09°28’11.9”

2.4 Data Processing

All acquired images were processed using plate-solving techniques to determine the right ascension and declination of the image center. For the alt-az pointing test, the plate-solved equatorial coordinates were converted into altitude and azimuth coordinates using Astropy, based on the observation site and time.

Pointing error was calculated as the difference between the commanded target coordinates and the plate-solved image center coordinates. For tracking analysis, the displacement of the image center relative to the initial frame was calculated for each time step (in the first image capture, the target star will be positioned in the center of the image).

2.5 Performance Metrics and Analysis

All data obtained from the data collection process will be processed to determine accuracy and precision. Accuracy indicates the closeness of a measurement to the correct or accepted value and is expressed in terms of measurement error or deviation. Precision describes the reproducibility of measurements, in other words, the closeness of the results obtained by the exact same method. In general, measurement accuracy can be assessed by repeating the measurements under identical conditions (Skoog, 2014).

The calculations will use Equation 2-1 to calculate measurement error:

$$E = x_i - x_t \qquad (2\text{-}1)$$

where E is the measurement error, $x_t x_t$ is the true value, and $x_i x_i$ is the measured value. To calculate the precision value, Equation 2-2 is used:

$$d = |x_i - \bar{x}| \qquad (2\text{-}2)$$

where d is the deviation value, and $\bar{x}$ is the average value from the number of measurements.

3. Result and Analysis

Pointing and tracking performance were evaluated using the procedures described in Section 2. The results are reported using standard angular metrics ($E \pm dE \pm d$) and expressed in degrees and arcminutes/arcseconds for clarity.

3.1 Pointing Performance in the Alt-Azimuth Coordinate System

The results show that the average azimuth pointing error is 1.600° ± 0.123°, corresponding to approximately 96.0′ ± 7.4′. For altitude pointing, the average error is 0.415° ± 0.048°, equivalent to 24.9′ ± 2.9.

Figure 3-1 illustrates the distribution of pointing errors across the tested alt-az grid. In general, pointing errors tend to increase at higher altitude angles, particularly above 70°. However, relatively lower errors are observed at azimuth angles of 90°, 180°, and 360°, even at high altitudes. This suggests that the pointing accuracy is influenced not only by altitude but also by the mechanical loading and orientation of the mount.

A single large pointing error of 7.8° was observed at an altitude of 80° and an azimuth of 270°. This value was retained in the analysis, as it reflects realistic operational conditions of a portable telescope system. The deviation is likely related to imperfect leveling during setup, imbalance of the optical tube and accessories, and environmental disturbances such as wind during image acquisition.

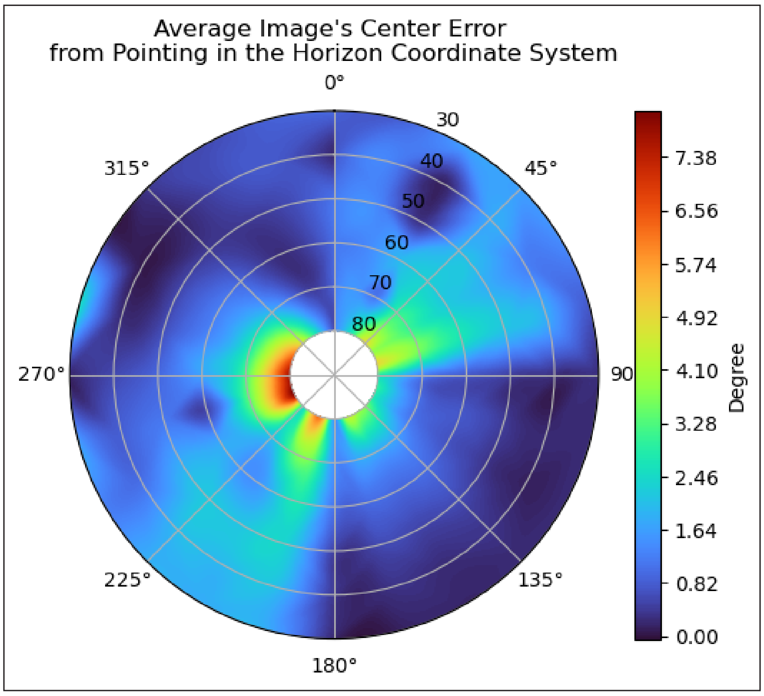

Figure 3-1: Pointing Error in Horizon Coordinate System.

3.2 Pointing Performance in the Equatorial Coordinate System

The equatorial pointing errors in RA vary from 0.19° to 0.74° or 11.4′ to 44.4′, and the DEC errors vary from 0.19° to 0.6° or 11.4′ to 44.4′. The overall mean equatorial pointing error is 0.451° ± 0.106°, corresponding to approximately 27.1′ ± 6.4′.

Figure 3-2 shows the distribution of equatorial pointing errors for each target star. The results indicate that the mount is generally able to place targets within a sub-degree accuracy across different sky regions.

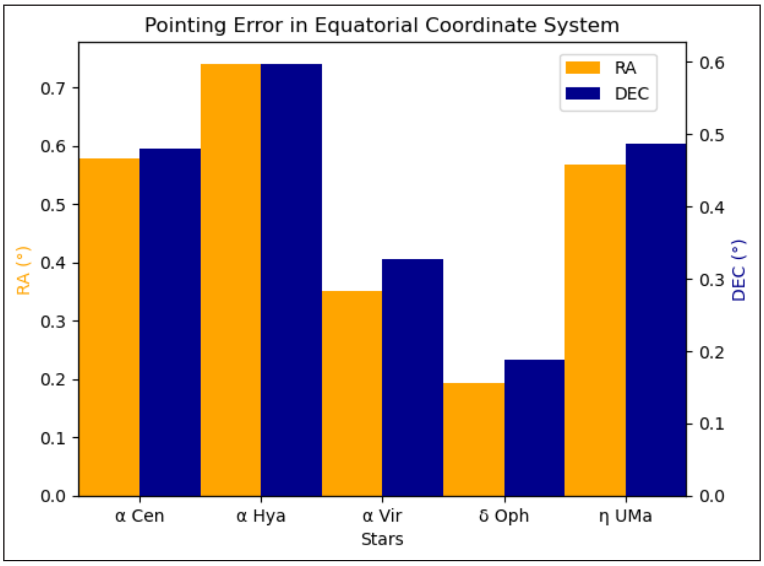

Figure 3-2: Pointing Error in Equatorial Coordinate System.

3.3 Tracking Performance

For Alpha Centauri, the displacement of the image center during tracking ranges from 0.032° to 1.1° in right ascension and 0.007° to 0.153° in declination, corresponding to approximately 1.9′ to 66.0′ (RA) and 0.4′ to 9.2′ (Dec). The tracking profile shows a periodic pattern, which is consistent with mechanical periodic error in the drive system.

For Beta Librae, the right ascension displacement ranges from 0.048° to 0.671° (2.9′ to 40.3′), while the declination displacement ranges from 0.144° to 0.587° (8.6′ to 35.2′). In this case, the declination drift increases gradually over time, whereas the right ascension drift remains relatively stable. This behavior suggests the combined effects of field rotation and mechanical imbalance inherent to the alt-az configuration.

For Tau Herculis, the displacement ranges from 0.372° to 0.406° in right ascension (22.3′ to 24.4′) and 0.17° to 0.49° in declination (10.2′ to 29.4′). Similar to Alpha Centauri, a periodic drift pattern is observed during tracking.

Across all tracking tests, the average tracking error is 0.213° ± 0.151°, corresponding to approximately 12.8′ ± 9.1′ (or 766.8″ ± 543.6″), with an RMS value of 942.7″ (15.7′). The derived tracking drift rates range from 22 to 36 arcseconds per minute, depending on the sky region and target declination.

Figures 3-3 (a), (c), and (e) show the tracking profile plots of three stars in three different sky directions, while Figures 3-3 (b), (d), and (f) show the plots of the relative displacement of the image center point in the tracking process of each target star.

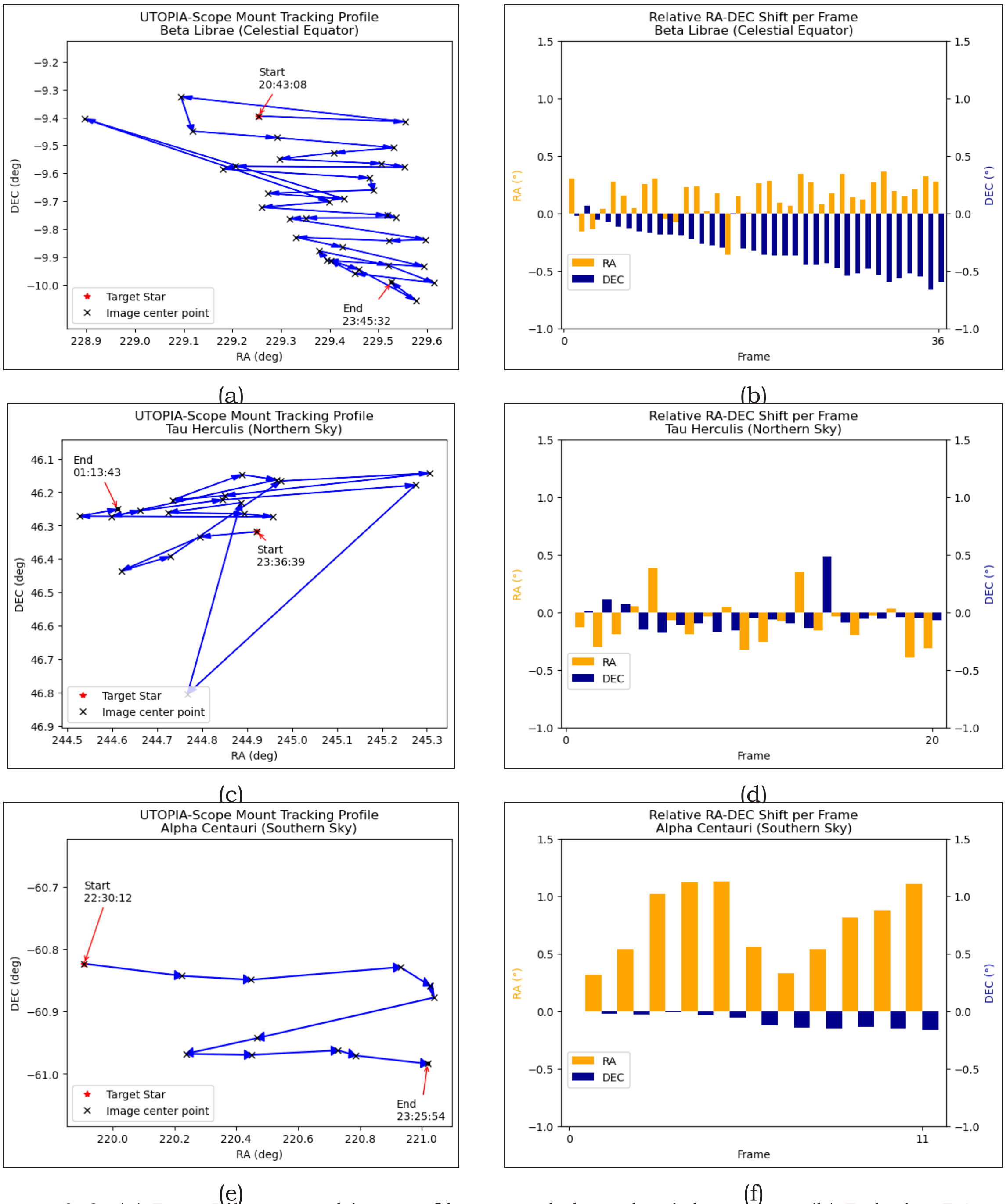

Figure 3-3: (a) Beta Librae tracking profile around the celestial equator, (b) Relative RA-DEC displacement of Beta Librae tracking, (c) Tau Herculis tracking profile in the northern sky, (d) Relative RA-DEC displacement of Tau Herculis tracking, (e) tracking profile in the southern sky, (f) Relative RA-DEC displacement of Alpha Centauri tracking.

4. Conclusions

This study presents a performance characterization of the UTOPIA-Scope, a low-cost DIY alt-az robotic telescope mount developed using aluminum structural components and 3D-printed strain-wave gears. The evaluation focused on pointing accuracy and tracking behavior based on observational tests carried out under realistic operating conditions.

The results show that the mount achieves average pointing errors of 1.600° ± 0.123° (96′ ± 7.4′) in azimuth, 0.415° ± 0.048° (24.9′ ± 2.9′) in altitude, and 0.451° ± 0.106° (27.1′ ± 6.4′) in equatorial pointing. Tracking tests indicate average drift rates of 22–36 arcseconds per minute, corresponding to approximately 0.37–0.60 arcminutes per minute, with total tracking errors on the order of 12–16 arcminutes, depending on the observed sky region. These values are consistent with unguided alt-az operation and reflect the mechanical characteristics of a compact and portable mount.

Based on this performance, the current version of the UTOPIA-Scope mount is suitable for visual observation and basic imaging applications, particularly when combined with plate-solving techniques. The results also highlight several areas for improvement, including more consistent leveling procedures, improved load balancing, mechanical reinforcement, and further tuning of the drive and control systems. Addressing these aspects is expected to reduce systematic pointing offsets and tracking drift.

The strain-wave gear design used in this mount is based on an open-source model. By providing quantitative performance metrics and documenting the current limitations, this work offers a clear reference for future development of accessible robotic telescope mounts for educational and small-scale scientific applications.

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Contributorship Statement

RAB is the main contributor to this paper. HPP, AZR, ABW, RWW, AAY, and AO proofreads the writing and suggests improvements.

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