High Efficiency Direct-drive Mount for Space Surveillance and NEO Applications

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Abstract

The design, manufacturing and field tests of a new astronomical telescope mount are the main topics of this paper. The new robotic mount dedicated for 0.5 m class telescopes is the first mount developed, developed and produced as fully Polish concept by engineers and researchers representing the automation and robotics discipline (Poznań University of Technology) and astronomy (Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences). The mount is an alt-azimuth fork-type design which allows tracking of typical astronomical targets (sidereal tracking) but also man made objects (satellite tracking). Thanks to a unique mechanical design based on direct drive motors and high precision encoders coupled with custom electronics and on-board software implementing modern control theory achievements it was possible to obtain very good trajectory tracking precision throughout the entire dynamic range defined by the user scenarios. Additionally, the used control algorithms are robust to some class of disturbances such as friction which in turn allows for very high precision tracking in a wide range of angular velocities—from quasi-static movements to high-velocity satellite tracking. The test-bed infrastructure of the system is located in a dedicated astronomical research laboratory at the Poznań University of Technology campus. Local, remote as well as automatic observations can be carried out in the facility.

Key words: Automated telescopes – Stellar tracking devices – Telescopes

Online material: color figures

1. Introduction

The development of autonomous telescopes (or even entire observatories) has become one of the most important branches of modern instrumental astronomy. By autonomous telescopes we understand devices capable of performing at least one observing night automatically based on a general outline given by the user. Many observatories, though, can operate without human assistance for weeks or months. This is a very important step ahead from traditional instrumental astronomy where the observer had to participate in the whole procedure during all clear nights in the year (in some observatories this is even 300 nights). This reduces the need of making tiring, expensive and lengthy observing sessions in remote observatories for the maintenance team. The trend to enable remote or automatic observations on older, larger instruments that have been used in a classical old-fashioned way is also visible, e.g., the Lowell Observatory 0.8-m Telescope (Buie 2010) or the 2.3-m telescope at Siding Spring Observatory (Mathewson et al. 2013). Autonomous telescopes are successfully used in search for a broad range of objects—binary stars, extra-solar planets, supernovas, gamma-ray bursts, etc.

Lately, however, a new area of application for optical observatories is becoming more pronounced: Space Situational Awareness (SSA). Space safety is becoming a concern of most space agencies in the world. SSA covers a broad range of activities related to space weather (SWE), near-Earth objects (NEO) and satellite and space debris—space surveillance. Both NEO and space surveillance require optical observing systems to carry out the tasks of detecting and tracking objects. In the same way as CCDs changed the scientific opportunities in the photographic plate era, now sCMOS cameras introduce new capabilities of building fast and responsive systems to cope with the requirements of SSA. Optics, electronics, mechanics and data processing—these all need to evolve in parallel.

Nowadays, continuous monitoring of objects which orbit around the Earth is particularly necessary. It is estimated that there are about 900,000 objects between 1 and 10 cm in size in the orbit around the Earth and 95% of them are space debris. Estimations are based on a statistical model called Master
(Meteoroid and Space Debris Terrestrial Environment Reference—Krag et al. 2002). In the USSPACECOM database 20 655 objects are classified and their orbits are described.\(^4\) Government and military institutions, and private companies around the world are responsible for orbit objects tracking and cataloging. Objects that are not active satellites cannot be controlled in any way from Earth, while large number of active satellites is deprived of this possibility. This means that their orbits require continuous monitoring.

Optical observation of artificial satellites consist in measuring the position of a satellite in a plane tangential to the celestial sphere, against the stars in the background. In particular, the tracking of satellites becomes challenging in the LEO range (Low Earth Orbits, full range of LEO is 160–2000 km), where the angular velocities of the satellites are significant. Under these conditions, the properties of classical mounts are insufficient.

It turns out that obtaining the expected observation results in the autonomous work regime require automated mounts which resemble systems commonly found in robotics. In fact, such mounts can be regarded as precise manipulators equipped with optical instruments as end-effectors. Hence, robotics can offer novel tools to support instrumental astronomy and SSA, see (Castro-Tirado 2010; Rastelli et al. 2019).

It is expected that a modern robotised mount should be able to operate in a wide velocity range. Natural stellar and non-stellar objects move in the sky at a speed relative to the observer which primarily results from a daily motion of the Earth with velocity equal to \(15^\circ h^{-1} = 7.27 \cdot 10^{-5} \text{ rad s}^{-1} = 15 \text{ arcsec s}^{-1}\). In comparison, satellites especially in low orbits, move at speeds of the order of \(2^\circ s^{-1}\). In addition, a fast reconfiguration of the mount with a speed up to 100 deg s\(^{-1}\) is also a valuable feature since it enables a significant reduction of intervals between observations of subsequent objects. Moreover, when tracking an object moving even at a small angular velocity near the Zenith (or Celestial Pole for equatorial configuration), the angular velocities in the mount’s axes increase significantly around the singularity point. This improves the efficiency of the robotic system as a whole and allows more images (and resulting measurements) to be acquired in time. Additionally, a fast response systems is suitable for multi sensor operation, e.g., according to the stare and chase scenario (Steindorfer et al. 2017). As a result, the expected dynamic range of motion speed can reach 1:20,000.

Another critical issue is the tracking precision which typically should be better than 1 arc second. This is due to the scale of the image projected on the camera sensor—for example one can roughly assume that 1 camera pixel corresponds to about 1 arc second (this value is chosen here as a general case estimate to illustrate the scale of the problem and is strongly dependent on the optical view angle and camera parameters). The investigated accuracy refers to the measurements in the external space, after taking into account the disturbances including wind or mechanical-optical system bending. In practice, this implies that control errors in the mount axes should not exceed several hundredth arcseconds. Tracking precision related to non-sidereal mode is of utmost importance as it directly influences the reachable astrometric precision of the reduced images.

The mentioned above requirements impose serious restrictions on the design of drive systems. In particular backlash-free solutions seems to be preferred here. For example, a direct drive system where a high torque motor is mounted on each axis itself can be employed. According to Andersen et al. (2003) and Gilmozzi & Spyromilio (2007) this approach has been applied successfully in many large alt-azimuth (alt-az) telescopes. In comparison to other drive mechanisms, in which the force is concentrated on a pinion or wheel, direct drives distribute the thrust along the structure, thus minimizing localized deformation and maximizing the structural stiffness. In addition, it has been reported, see Bely (2006), that direct drives are quite tolerant to mechanical misalignments which increase the system durability and reduce telescope installation time.

New observatories that are capable of space surveillance activities are being established as the market grows, existing ones are being adapted. This happens in parallel with the development of new hardware, electronics, optics and control systems. The Mobile Aerial Tracking and Imaging System (MAtiS) for Aeronautical Research (Banks et al. 2004) consists of a horizontal mount that has been developed for tracking objects that move at non-sidereal speeds, such as spacecraft, aircraft, ballistic objects. It can be fitted with various optical instruments and work in a closed video servo loop (optical tracker) or open-loop based on pre-computed azimuth and elevation coordinates.

Another project that needs to be mentioned here is the Las Cumbres Observatory, a network of multiple robotic telescopes spread around the world (Brown et al. 2013). The telescopes in the network range from 0.4-m to 2.0-m in diameter and host an array of instruments. Particularly interesting from this work’s perspective are the 0.4 m and 1.0 m scalable C-ring mount designs that share the same hardware drive and software control mechanisms (Dubberley 2010). Part of the network is also used for satellite tracking programs. The impressive size of the network constituting custom designed mounts and telescopes shows that made-to-measure hardware can be considered an asset for specialized observatories, even though there exist off-the-shelf solutions, such as Astelco, PlaneWave, ASA or 10Micron. Some of these manufacturers offer backlash-free, direct drive mounts capable of satellite tracking that are used in advanced observatories around the world. All of these, however, are closed systems that do not allow for research activities concerning the control system to be carried out easily. Limited or no access to the control algorithms and on-board software is the major limiting factor if one wants to

\(^4\) Statistics source: https://www.space-track.org, accessed 2020 May 26.
push the development to a higher level from the perspective of dynamics, efficiency and new control algorithms.

In this paper we present results of research concerning a new direct-drive mount for optical robotic telescope applications, that are on par with modern SSA expectations. Here we significantly extend results from (Kozłowski et al. 2020) where an initial prototype of an robotised mount is outlined. First, we consider the design and construction of an automated astronomical telescopic mount which is capable of supporting and control of an astronomical telescope of a 0.5 m class. The mount ensures accurate pointing of the telescope and its instruments track the motion of stars and satellites as the Earth rotates. We do believe that the accuracy of satellites tracking ensured by our system is comparable or even better than the accuracy reported in (Rastelli et al. 2019). The design concerns the preparation of the mechanical structure of the mount as well as motion control system along with low and high software level. Second, we outline a structure of a new research laboratory called SkyLab designed for astronomical observations. In this laboratory the new mount is tested and continuously improved. The observatory is a modern testbed where new hardware and software solutions to support autonomous work are investigated.

It is noteworthy that the presented new mount has been designed from the ground up taking into account high dynamics operations. Although there are commercial, off-the-shelf solutions available, they do not always perform as advertised. Moreover, these components are black boxes with little or no access to the internals. This can be a limiting factor in case of advanced applications that require a tight fit between the mechanical system, control electronics and instrumentation (e.g., closed loop video tracking, polarimetry or spectroscopy of fast-moving objects in orbit). By showing the design process, appearing challenges and proposed solutions, we intend to show that there is room for much improvement and therefore an opportunity to build well optimized systems that can fully exploit the potential of modern instruments.

The paper is organized as follows. Section 2 discusses the assumptions for the design of the mechanical part and the design in general. In Section 3, the drive system and the solution used for precise position measurement are characterized. Section 4 deals with the control algorithm of the drive axis with an adaptive structure. In Section 5 the commissioning and on-sky test results are presented. The last chapter summarizes the work.

2. Mechanical Design

The construction of the astronomical mount is illustrated in Figure 1. The designed mount is of an alt-az fork type and provides a symmetrical telescope mounting fork, which enables fastening of the telescope from both sides. It allows for independent movement in up-down and left-right directions, so one axis of rotational degree of freedom is parallel to the horizon, whereas the second axis of rotational degree of freedom is perpendicular to the horizon. The mount is capable to perform the tracking of objects on the sky with use of telescopes of the class 0.5 m, and the parameters of tracking are given in Table 1. In this table we also present the parameters which were assumed for mechanical design process.

We distinguish four basic construction elements in the mount, which are presented in Figure 1. The base unit (Z1) is a supporting element which is grounded. It also contains a mounting socket for the vertical axis unit (Z2). The vertical axis unit (Z2) performs the rotation around VA (vertical axis) and it contains the bearing, the mounting flanges, the driving motor and the system responsible for an angle position measurement. The vertical axis unit (Z2) is connected with the support of the horizontal axis unit (Z3). This element is the base for two separate half-shafts, which are a part of the horizontal axis unit (Z4). In the astronomical nomenclature the support of the horizontal axis unit (Z3) is often called a fork, because it is built in the shape of a pitchfork. As it was said, the horizontal axis unit (Z4) consists of two half-shafts, where each of them is connected to the arms of the fork. Half-shafts provide the possibility of the rotation of HA (horizontal axis) throughout a set of bearings. Additionally, one of the half-shafts has the driving motor, which provides the drive of HA, and the opposite half-shaft consists of a measuring system of the rotational position of HA.

2.1. Vertical Axis Unit

The vertical axis unit (Z2) depicted in Figure 2 consists of: the discs break unit, the angle measuring unit, the electrical motor, the bearing set, the bearing housing and the supporting slave of the support of the horizontal axis unit. The main part of the bearing set (element 4) is the bearing provided by Franke company. It is a four point contact bearing which can handle mixed loads. The bearing set is equipped with an aluminum fixing flanges. The supporting slave of the support of the horizontal axis unit (element 6) is the fastening element for this support of the horizontal axis unit (Z3), and it is fixed in the inner ring of the bearing. Moreover, the supporting slave of the support of the horizontal axis unit is a transmission shaft which drives the support of the horizontal axis unit (Z3).

The electrical motor stator (element 3) is fixed with the outer part of the bearing set, whereas the rotor is fixed with the supporting slave of the support of the horizontal axis unit. The angle measuring unit (element 2) of the vertical axis unit consists of the measuring ring and reading heads, which read the bare code from the ring. It provides the absolute angle measurement in VA. The measuring ring is connected with the supporting slave where the reading heads are mounted on the supporting rods connected with the bearing housing (element 5). Here, we only describe the connection between the elements of the vertical axis unit. The details about electrical motor are described further in Section 3, whereas the measuring unit is
described in Section 3.2. The vertical axis unit is also equipped with the rotation limiters which restrict the rotation of the support of the horizontal axis unit (Z3) in the range of 7 rad i.e., 3.5 rad clockwise and 3.5 rad counter-clockwise from the base position. The rotation limitation is realized by the set of four limit switches along with a custom design sliding bumper mechanism equipped with pneumatic dampers. This rotation limiters are mounted beneath the supporting slave and they are not visible in Figure 2. At the bottom of the vertical axis unit we have the discs break unit (element 1) which provides a possibility of breaking the axis rotation in case of emergency.

### 2.2. Support of the Horizontal Axis Unit

The support of the horizontal axis unit (Z3) is presented in Figure 1 and as a standalone element in Figure 3. It is realized as a single solid element and was manufactured as a cast from the special aluminum alloy. From the bottom side of the support of the horizontal axis unit (Z3) is connected with the supporting slave, whereas from the top side it is joined with elements of the horizontal axis unit, that is the active half shaft support (AHSS) and the passive half shaft support (PHSS). More in-depth description of AHSS and PHSS is presented in Section 2.3. Both upper endings of the support of the horizontal axis unit (Z3) have key locks which allows for concentric fixation of AHSS and PHSS. Such a aligned fixation is an essential thing assuring proper rotation of HA. At the level of design process, a shape and a mass optimization of the support of the horizontal axis unit (Z3) was performed taking into account specific properties of movement, durability and functionality.

### 2.3. Horizontal Axis Unit

The designed horizontal axis unit (Z4) consists of two half shaft units which constitute HA bearings. The first half shaft is AHSS and it is presented in Figure 4, whereas the second is PHSS and it is presented in Figure 5. They are connected with the telescope throughout the telescope handlers shown in Figure 6. The rotating parts of AHSS, PHSS together with

![Figure 1](image1.png)
**Figure 1.** The prototype astronomical mount with a 0.5 m telescope in the campus observatory: Z1—base unit, Z2—vertical axis unit, Z3—support of the horizontal axis unit, Z4—horizontal axis unit, VA—mount vertical axis, HA—mount horizontal axis.

![Figure 2](image2.png)
**Figure 2.** Vertical axis unit model: 1—discs break unit, 2—angle measuring unit, 3—electrical motor, 4—bearing set, 5—bearing housing, 6—Z3 supporting slave.

(A color version of this figure is available in the online journal.)

| Parameter Assumed for the Design Process | Value          |
|-----------------------------------------|----------------|
| Maximum axes (both) velocity            | 0.52 rad s⁻¹  |
| Time of achieving max. axes vel.        | 0.2 s          |
| Maximum axes acceleration               | 2.62 rad s⁻²  |

| Parameter Physically Obtained           | Value          |
|-----------------------------------------|----------------|
| Maximum axes velocity                   | 1.74 rad s⁻¹  |
| Maximum axes acceleration               | 1.30 rad s⁻²  |
| Maximum axes deceleration               | 1.70 rad s⁻²  |

![Table 1](image3.png)
telescope handlers and the telescope itself constitute the rotational shaft. This shaft provides a rotational degree of freedom which realises the rotation of the telescope in the horizontal axis. AHSS and PHSS are designed assuming that the telescope construction cannot transfer any loads and it cannot be treated as an element for concentricity maintenance for HA.

AHSS is equipped with an electrical motor (described in Section 3), which provides the driving torque to the telescope. AHSS is also equipped with angle limiters and limit sensors. The usable range of this axis is about $\pi$ rad, i.e., from the horizon up to the zenith and down to the horizon. PHSS contains the angle measuring unit (discussed in Section 3.2). Both units are equipped with double angular contact bearings provided by the Keydon company. The telescope handlers are connected with AHSS and PHSS by rounded fixing flanges with use of prismatic cranes attaching a telescope to a mount.

In case of using a different telescope than the one considered in this paper, it is easy to replace the telescope handlers considered here by another one.
An important feature of the designed horizontal axis unit is the possibility of light beam guidance from the telescope mirror to the camera sensor directly through the center of AHSS or PHSS. This feature is provided by the hollow shaft design of AHSS and PHSS, what can be seen in Figures 4 and 5. This functionality enables image capturing outside the telescope unit.

3. Motor Drivers

3.1. Driving Motors and Motor Power Control Unit

When selecting the drive structure, the basic design requirements were considered, which include no backlash, a wide speed range as well as durability and operational safety. Taking into account these aspects we decided to use direct gearless drive supported by electric permanent magnets brushless synchronous motors (PMSMs). The same PMSMs are selected for driving the horizontal and vertical axis of the mount and they were provided by Alxion company. Due to special demands, the Alxion company prepared a customized version of motor unit which has different parameters than the motors offered by the Alxion on the market. The essential parameters of the employed PMSMs are: nominal drive torque 50 Nm, maximal drive torque 110 Nm, nominal voltage 33 V and nominal current 20 A. Since motors are frameless, the construction of the vertical axis unit and the horizontal axis unit has to provide the whole housing for the parts of the motors. Some details about fixation of these elements were given in Section 2.1. In particular, a proper integration of the motors parts required a solid fixation of rotors and stators to the mechanics of the mount in order to achieve the desired concentricity of axes.

The motors are governed by an electronic unit designed specially for this project, where its structure is presented in Figure 7. This unit takes advantage of the Texas Instruments Three Phase PMSM Motor Module (Power amplifier) and AM4379 Secure Boot Module (CPU Cortex A9). The power supply module provides the DC bus supply voltage for Power Management Unit (PMU) from which the power amplifiers are supplied. The PMU is also responsible for dissipating the electric energy generated from the kinetic energy of the rotating mechanism.

Power amplifiers, marked in Figure 7 as 3-PPS (3-Phase power stage), exploit a three-phase Voltage Source Inverter structure. The measurement of the phase currents are supported by external high-speed 16-bit ADCs (Analog-to-digital Converters) that makes it possible to obtain high quality data in a wide current range.

The CPU Cortex A9 is a main processor which support real-time control of the entire system, see Section 4. Software of the controller is written in C++ and is partially supported by TIRRTOS (Texas Instruments Real Time Operating System).

3.2. Position Measurement System

The measurement of the horizontal and vertical axes angular position is performed by the measurement units (MUs) designed with use of sensors provided by Renishaw company. Both measuring units (marked as MU1 and MU2 and presented in the block diagram in Figure 7) consist of a measuring ring and four reading heads, placed symmetrically around the ring. This solution helps to reduce the positioning inaccuracy as it is reported in (Janiszewski & Kiełczewski 2017). Each MU provides the angle position with accuracy better than 0.01 arc second. Information from the measuring heads is transmitted to the control system with use of serial communication with a BISS-C protocol. Since the main CPU does not support the BISS-C communication standard, the additional FPGA module (presented in Figure 7) is responsible for collecting data from each reading head and sending the preprocessed data to the CPU.

MU1 is presented in Figure 2 as the element 2, where the reading heads are covered by other elements. MU2 is presented in Figure 5. In this figure the measuring ring is visible on the front face of the system and it is surrounded by the four reading heads placed symmetrically, see element 3.

4. Control System

4.1. Control Objectives

Assume that the mount and the telescope are composed of rigid bodies and their kinematic model, which describes a map between the joint space and the external space defined with respect to the optical axis of the telescope, is fully known. Then it is possible to ensure a proper tracking of sky objects indirectly by controlling the mount at the joint/drive level. Additionally, due to the employed mechanical structure, dynamical couplings between two links are strongly limited. As a result one can apply a decentralized control strategy for which each joint is controlled independently, see (Patelski & Dutkiewicz 2020).
In astronomical applications, achieving a high positioning accuracy becomes an essential requirement which is far more critical than in typical industrial applications. In addition, the demand for a high range of speeds during set-up mode (reaching the set point) and low speeds in the task of tracking star-like objects and artificial satellites should be taken into account.

It turns out that classical PID-like methods, when applied for motion control of a telescope mount, can be insufficient due to their sensitivity to internal and external disturbances. For this reason, it seems to be required to use new servo control techniques which are more robust to model uncertainties. The source of these uncertainties include the occurrence of a friction phenomenon, see Piasek et al. (2019). Another source of internal model disturbances is a limited knowledge of the mount inertial parameters and the influence of gravity resulting from the unbalance of the telescope and the attached instruments. In addition, stochastic external influences such as wind blows are also to be expected.

4.2. The Tracking Controller Design

To accomplish the required control objectives we design a motion controller taking advantage of the Active Disturbance Rejection (ADR) paradigm originally introduced by Han (2009). The methodology used here employs a High-Gain Extended State Observer (ESO) which makes it possible to estimate a matched disturbance. The disturbance estimate is then used to approximately reject uncertainty terms from closed-loop dynamics.

The mathematical description of the mount model is performed as a two degrees of freedom system. First degree concerns the rotation of the mount around VA, see Figure 1, and it is described by $\varphi_1$. The second degree of freedom represents the rotation of the mount around HA and it is described by $\varphi_2$. The moments of inertia around VA and HA are defined by $J_1$ and $J_2$, respectively. Each axis is driven by an independent actuator (an electrical motor), while $\tau_1$ and $\tau_2$ are torques exerted on VA and HA, respectively.

The controller is designed based on the following fundamental model of the mount
\[
\varphi = \Delta + J^{-1}(\varphi)\tau, \tag{1}
\]
where $\varphi = [\varphi_1 \quad \varphi_2]^T \in S^1 \times S^1$ is a configuration, $J(\varphi) = \text{diag}[J_1(\varphi), J_2(\varphi)]$ is a diagonal inertia matrix, and $\tau = [\tau_1 \quad \tau_2]^T \in \mathbb{R}^2$ is the torque input exerted by the motors. The term $\Delta = [\Delta_1 \quad \Delta_2]^T \in \mathbb{R}^2$ stands for dynamic couplings, including in particular the Coriolis and centrifugal forces, the friction phenomena, gravity terms and other lumped disturbances. To further facilitate the subsequent control design, we assume that $\Delta_i$ is a bounded function with a bounded derivative in an open interval (at least in a neighborhood of the operating point).

Taking into account the considered mechanical structure and Equation (1) one can assume that both axes are loosely coupled at least in a range of small velocities. Then it becomes reasonable to design the control system taking advantage of two independent feedbacks. We investigate a distributed controller assuming that, due to the used sensors, the configuration $\varphi$ is the only measured variable. In spite of that, the state of system (1) and additive components $\Delta_1$ and $\Delta_2$ can be estimated throughout two high gains linear observers defined by:

\[
\dot{\hat{\varphi}}_i = \begin{bmatrix} \hat{\varphi}_{i2} \\ \hat{\varphi}_{i3} + J_i^{-1}(\varphi_1)\tau_1 \\ L_i(\varphi_i - \hat{\varphi}_i) \end{bmatrix}, \quad i = 1, 2, \tag{2}
\]

where $\hat{\varphi}_i = [\hat{\varphi}_{i1} \hat{\varphi}_{i2} \hat{\varphi}_{i3}]^T$ represents the estimate of the angle, the angular velocity and the disturbance, respectively, whereas $L_i \in \mathbb{R}^3$ defines gains. For example, the following tuning strategy can be employed: $L_i = [3\omega_0, 3\omega_0, \omega_0]^T$, where $\omega_0 > 0$ can be interpreted as the observer bandwidth.

In the application considered here, it is essential to increase the feedback sensitivity with respect to small tracking errors. Theoretically, one could use the variable control structure approach, however, it may produce a significant chattering effect which deteriorates the tracking performance. To overcome this difficulty and to improve the tracking precision we employed a nonlinear feedback using fractional exponents, see Galicki (2015) and Su & Swevers (2014). Consequently, assuming that $\hat{\varphi}_i = [\hat{\varphi}_{i1} \hat{\varphi}_{i2} \hat{\varphi}_{i3}]^T \in S^1 \times S^1$ denotes the reference trajectory, while $\varphi_1$ is a function of class $C^2$, we propose the following tracking controller:

\[
\tau = J(\varphi)(-K_P[\varphi - \varphi_1]^p - K_D[z_2 - \varphi_1]^p - z_3 + \varphi_1), \tag{3}
\]

where $z_i = [\hat{\varphi}_{il} \hat{\varphi}_{i2l} \hat{\varphi}_{i3l}]^T \in \mathbb{R}^2$, $l = 1, 2$, $K_P, K_D \in \mathbb{R}^{2 \times 2}$ are positive definite gain matrices, $\alpha_p = [\alpha_{p1} \alpha_{p2}]^T$, $\alpha_v = [\alpha_{v1} \alpha_{v2}]^T \in \mathbb{R}^2$ with $\alpha_{pv} \in (0, 1)$ and $\alpha_{vi} = \alpha_{pi}/(\alpha_{pi} + 1)$. In order to make the notation more compact in formula (3) we employ the following non-standard brackets operator

\[
\forall \xi \in \mathbb{R}^2, \quad [\xi]^p = \begin{bmatrix} |\xi_1|^p \text{sgn}(\xi_1) \\ |\xi_2|^p \text{sgn}(\xi_2) \end{bmatrix} \in \mathbb{R}^2, \tag{4}
\]

while $\alpha = [\alpha_{11} \alpha_{21}]^T$, $\alpha_{ij} > 0$, $j = 1, 2, \lfloor i \rfloor$ is the absolute value of the real function, $\text{sgn}$ stands for the sign function.

In Figure 8 we present an essential control structure for $i^{th}$ axis assuming that gain matrices are diagonal and satisfy $K_p = \text{diag}[k_{p1}, k_{p2}]$, $K_D = \text{diag}[k_{d1}, k_{d2}]$. The reference trajectory $\varphi_i$ along with its first and second order derivatives is determined by a generator that governs motion of the mount. The position and velocity errors are nonlinearly mapped according to formula (4) which makes it possible to increase
the sensitivity to errors in a vicinity of zero. Since a direct measurement of velocity $\dot{\varphi}$ is unavailable the corresponding error component is computed using the velocity estimate $\dot{\hat{z}}_3$ which is provided by the observer ESO. However, the main purpose of the observer is to estimate the additive disturbance $\Delta_i(t)$ which represents unmodeled part of the mount dynamics. In the considered case, it can be shown that $\dot{\hat{z}}_3$ follows the unknown trajectory $\Delta_i$. As a result, the estimate $\dot{\hat{z}}_3$ is used to partially reject the disturbance $\Delta_i$ in a local loop. Due to this approach the total disturbance in the main control path becomes a residual term which makes it possible to improve the control performance considerably. Although in real scenarios the observer bandwidth has to be limited due to stability issues imposed by delays in the control loop and the sensitivity to measurement noises, still the considered control approach is highly competitive with classical methods based on integral action controllers including a PID-like structure.

Taking into account implementation issues it should be noted that the torque $\tau$ described by the formula (3) is not a real control input due to used actuators in the form of PMSMs which require an additional current control loop. Thus, we take advantage of a cascade control structure and similarly as in (Patelski & Pazderski 2019) we assume that $\tau$ is the reference signal $\tau_d$ for classic PI controllers with an anti-windup protection (called as the motor controller in Figure 9).

### 4.3. General Structure

The structure of the entire control system is presented in Figure 9 and consists of two timescale blocks. The tracking controller works with sampling frequency $f_s = 10$ kHz, while the reference generator is computed in an external loop with frequency up to 50 Hz.

In order to cope with different timescales a polynomial interpolator is coupled with the tracking controller. It is responsible for generating desired trajectories $\varphi_r$ specified for each axis of the mount. These internal trajectories are computed based on a set of discrete points determined by the external reference generator. It is important to emphasize that the motion controller operates only in the tracking mode and no dedicated set point stabilization model is used. Therefore, when

![Figure 8. Block diagram of the control algorithm defined for $i^{th}$ axis which is based on a nonlinear PD controller supported by a linear Extended State Observer (ESO).](image)

![Figure 9. Block structure of the control system algorithm.](image)
a new observation goal is chosen, the auxiliary trajectory which connects the current configuration with the desired configuration is computed in the on-line regime. Such an approach enables attenuating rapid transient states and allows for a safe and fast repositioning of the mount.

The important part of the generator is a submodule which maps trajectories \( w \) defined in the task space, namely using astronomical coordinates, to the internal (joint) coordinate space of the mount. It is important to note that such a map is highly nonlinear and is defined based on nominal kinematic parameters of the mount as well as it takes into account residual effects such as imprecise fabrication of the mechanism (including optical parts), bending of the structure, etc. Hence, the determination of nonlinear kinematic model (also known as pointing-model) requires a precise calibration taking into account real observations. More details are provided in Section 5.2.2.

### 4.4. Properties of the Control System in the Frequency Domain

To evaluate properties of the mount we conducted experiments in the open- and closed-loop regime.

In the first experiment we used a chirp torque input applied to each joint individually. The signal amplitude was set to 10 Nm for the horizontal axis and 20 Nm for the vertical axis, respectively. During the experiment angular positions were recorded. Based on that, the frequency-response of the considered mechanical structure was estimated. From Figure 10 one can easily detect resonance frequencies at 10–12, 26 Hz and 34 Hz. In particular, resonances become evident for the vertical axis where natural frequencies of the mount fork and elements attached to it are dominant.

In the next experiment the stabilization of axes at fixed configurations was taken into account. The selected parameters of the controllers are collected in Table 2. The spectrum of errors in two axes in the steady-state are presented in Figure 11. It can be observed that dominant frequencies are concentrated in the range 8–12 Hz.

### 4.5. Experimental Evaluation of the Control System in the Time Domain

In the experiment discussed here a high-speed repositioning of the mount combined with a slow-velocity tracking regime was investigated. It was assumed that initial azimuth and elevation were to be increased by 59 deg and 16 deg, respectively. The axes velocities, torques \( \tau_d \) and tracking errors are shown in Figures 12–14. The reposition phase starts in 0.2 s and lasts up to about 1.5 s. Later the reference trajectory is changed smoothly in order to track a star without stopping the mount. Maximum values of velocities in HA and

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**Table 2**

| Parameter | VA (1) | HA (2) |
|-----------|--------|--------|
| \( \alpha_{ip} \) | 0.85 | 0.85 |
| \( k_{ip} \) | 100 | 225 |
| \( k_{iv} \) | 24 | 36 |
| \( \omega_{bi} \) | 140 | 400 |
VA are 85 deg/s and 22.5 deg/s, respectively. From Figure 14 one can conclude that the settling time is relatively small. To be more precise, 0.5 s after the end of a rapid transition phase of the mount, the upper bound of the tracking errors becomes less than 2 asec. Next, in the time range 3–4 s shown in Figure 14 rms values of errors in HA and VA are 0.145 and 0.071 asec, respectively. Taking into account Figure 13 one can observe that the torque signals are relatively smooth and no significant oscillations occur. Such a behavior confirms good stability properties of the closed-loop system.

5. On-sky Commissioning

In this section we describe the on-sky test that have been conducted to verify the project requirements.

SkyLab, established in 2018 by the Institute of Automation and Robotics (IAR), is a fully fledged optical astronomical observatory owned and operated by the Poznań University of Technology that has been designed to be a research laboratory with infrastructure to test new hardware and software solutions developed by a team of engineers, computer scientists and astronomers involved in space-related projects carried out at the University. SkyLab facility is presented in Figure 15.

Despite being situated not far from the city center and subject to considerable light-pollution, the site is a very convenient to test astronomical equipment on-sky. The vicinity of electronic and mechanical workshops as well as convenient access for University staff is crucial when working on R&D projects.

5.1. Observatory Equipment

The observatory is equipped with necessary systems to allow remote, manual and fully automatic operation. The dome is located on the roof of a 2-floor building. The construction has been designed such a way that an instrument weighing up to 2000 kg can be installed in the dome in the future. The dome is a 4.5 m fibreglass clamshell construction, well suited for tracking of fast moving objects. Nearby buildings party obscure the Southern horizon at elevations lower than 15 deg. The view is unobstructed otherwise. The existing structure of the building has been strengthened and adjusted from the footings upwards to carry the load of the new facility. The dome is raised 120 cm above the concrete pad. A server-type lifted floor has been installed, so that the volume below is easily accessible. The main control rack cabinet as well as dome electronics are installed under the floor. Two weather stations are used to measure ambient conditions: precipitation, relative humidity, temperature, wind speed and direction and cloud base. One rain detector is hard-wired to the dome controller for greater security. Additional temperature and relative humidity sensors are installed inside the dome. Signals from the weather station and internal sensors are read and analyzed by a PLC-based safety system. Whenever any of the parameters is out of range, the dome closes. Additionally, the system makes all data available via OPC-UA to the observatory control software. Table 3 summarizes the equipment currently installed in the observatory. A 0.51 m f/6.8 Corrected Dall–Kirkham telescope is used for mount testing. Three imaging cameras are available: an FLI PL16803 CCD 4096 × 4096 9 μm pixels (default...
equipment), a KL4040 sCMOS 4096 × 4096 9 μm pixels (kindly made available for the commissioning period by the Nicolaus Copernicus Astronomical Centre) and a TIS DMK33GX174 GigE 1920 × 1200 5.86 μm pixels industrial camera. The KL4040 provides much better temporal resolution while utilizing the entire available field of view of the instrument, hence is well suited for testing the performance of the mount in space surveillance applications. The DMK33GX174 has a much smaller detector and thus a much smaller field of view—11.2 × 7.0 arcmin compared to 36.9 × 36.9 arcmin for the other 4K detectors, but allows for fast imaging above 100 FPS when cropped.

5.2. Software

Three layers are responsible for controlling the mount: (1) Abot, which is the high level control system of the entire observatory, (2) VirtualStar, a middle-level client/server application that is responsible for communication with the mount driver and (3) the mount driver itself (low level). The mount driver is the only layer that guarantees real-time operation. The layers are described in detail in the subsequent sections, from the top-level toward the low-level. Abot has been delivered as a commercial product, all other software components have been developed specifically for the project.

5.2.1. Abot

The observatory as a whole is managed by Abot, a commercial software package designed specifically for robotic observatories. Abot manages multiple observatories around the world, e.g., the Solaris Network (Kozlowski et al. 2017), MeerLICHT and BlackGEM (Bloemen et al. 2016). It includes software drivers for all devices installed in the observatory. These are integrated in specialised hubs that are responsible for controlling the operation of the observatory. The service-oriented architecture supports all typical scenarios of operation: flatfielding, automatic focusing, observing program execution, data storage and visualisation and extensive security—both in terms of hardware safety and user access (e.g credentials). Abot can operate in a fully automatic mode, where observing plans are executed without supervision or in a manual mode, where selected components are accessed and controlled via the services by the operator. High level commands, such as slewing to a target, sidereal tracking, satellite tracking, pulse guiding are passed on to the to VirtualStar middle-level controller.

5.2.2. VirtualStar

VirtualStar, custom software developed especially for this project, runs on a single board computer, but not in real-time regime. Commands received from Abot are processed within VirtualStar so that a trajectory is generated. For example, when a slew to equatorial coordinates command is received, the following steps are followed:

1. Transformation of equatorial coordinates to horizontal coordinates using SOFA (IAU SOFA Board 2019).
2. Transformation of horizontal coordinates to joint coordinates by applying the pointing model.
3. Computation of a series of trajectory points, each of which contains positions and velocities in joints and a relative timestamp when the trajectory point must be reached.
4. The list of trajectory points is uploaded to the low-level driver and a start command is sent to initiate the trajectory.

The same process happens when a satellite trajectory is computed, but desired coordinates are computed using the SGP4 code based on the TLE data provided from the top level controller. The Simplified General Perturbation (SGP) models are operational since the early 1970s. These routines (here used in version 4, Vallado & Crawford 2008) allow one to compute the position of an object in Earth’s orbit as observed from a given place at a given moment of time based on aforementioned orbital data.

5.2.3. Axes Driver

The trajectory points received from VirtualStar are internally interpolated and fed to the control loop. The driver communicates with the middle-level controller over a serial link using a custom Modbus-inspired protocol. Since the middle-level controller is essentially part of the control system, it should be treated as a black box.

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5 TLE—Two-line element set—data format that encodes the list of orbital elements of an Earth-orbiting object for a given epoch.
The zero time-value corresponds to the time instant when the star errors recorded in the external and internal spaces are depicted. However, in the time range 0-0.5 s differences similar after 0.5 s, namely when the transient response is almost completed. It can be seen that plots from the parking position to star HF116957 and immediately start increased by 58 deg and 50 deg, respectively, in order to slew from the observer coordinate system. It is responsible for realizing the control loop of both motors.

5.3. Sidereal Tracking

The considered mount enables fast repositioning from one observation goal to another. The performance of the system in the external space at the final stage of the mount repositioning. In the investigated scenario it was assumed that the initial azimuth and elevation were to be increased by 58 deg and 50 deg, respectively, in order to slew from the parking position to star HF116957 and immediately start sidereal tracking. The duration of the reposition phase is about 2.75 s. At the end of this phase the star was being observed by an industrial camera (DMK33GX174) in cropped configuration 912 × 900 pixels at approximately 67 FPS. The result of the last phase of this experiment is presented in Figure 16 where errors recorded in the external and internal spaces are depicted. The zero time-value corresponds to the time instant when the star could be properly detected by the camera. It can be seen that plots based on measurements from the encoders and the camera are similar after 0.5 s, namely when the transient response is almost completed. However, in the time range 0-0.5 s differences between internal and external trajectories can be easily noticed. It seems to be reasonable to state that these differences result from relatively long time camera exposure, the jitter effect, as well as a deformation of mechanical and optical elements of the telescope and the mount. Similarly as for experiments discussed in Section 4.4 the slewing and tracking trajectories are in fact one trajectory, therefore a classical settling time parameter of the mount is difficult to define. It can be clearly seen, however, that it takes approximately 0.5 s from when the star arrives in the desired position and is stably tracked. This highly competitive performance is a valuable addition to the high dynamics of the mount.

The axis driver is highly integrated with the hardware (see Section 4.3 for details) and operates in the mount joint coordinate system. It is responsible for realizing the control loop of both motors.

| Target          | equatorial (J2000) | horizontal  |
|-----------------|-------------------|-------------|
| ID              | α                 | δ           | A            | h              |
| HD116957        | 13°26′16″168      | 46°01′40″78 | 255°19′53″6  | 73°53′21″0     |
| HD183030        | 17°16′54″181      | 89°02′15″6  | 358°27′42″6  | 52°44′28″0     |
| Deneb           | 20°41′25″192      | 45°16′49″3  | 191°21′13″8  | 82°49′36″7     |
| 61 Aql           | 19°56′14″30       | 11°25′25″5  | 190°11′22″7  | 48°42′54″8     |

5.4. Satellite Tracking

The alt-az mount that is the main subject of this paper has been designed with space surveillance in mind—hence the selection of direct drives and absolute encoders. To test the...
performance of the mount we have selected two satellite targets on low Earth orbits:

1. NORAD ID 25910: perigree 1553.4 km,
2. NORAD ID 43550: perigree 362.1 km.

Data acquisition and processing has been identical as in case of stellar targets with one exception—the integration time had to be lengthened to 500 ms to get an image of the satellite with a good SNR. Test results are shown in Figures 20 and 21.

6. Summary

In this paper we have presented the design, production and commissioning of a robotic alt-az telescope mount that delivers high performance in terms of dynamics and precision. The long-term goal of the project was to establish a research facility that would allow implementing and testing advanced concepts in the area of control theory, astronomy, software, mechanics and electronics. The currently deployed system is capable of sidereal tracking with sub arc second precision as well as satellite tracking of objects on all orbital altitudes. Having a research-grade astronomical observatory equipped with a custom designed advanced telescope mount opens new fields of research and operation capabilities, e.g., closed loop optical tracking, high speed imaging, laser communication, advanced space surveillance related surveys. All these require access to all levels of the control system, from mechanics, via electronics and on-board software to end-user interfaces. We have shown that it is possible to develop a unique and state of the art system.
in limited time thanks to the contribution of engineers and scientists from various specializations. The system will continue to serve as a test-bed and, part-time, provide data for end-users.

### 6.1. Space Surveillance and Astronomical Community Impact

In the era of a rapid increase of spacecraft in orbit, ground-based observations are becoming a very important source of data concerning orbital traffic. This applies to all orbital altitudes—from LEO to GEO. Advances in digital detectors, vision systems and data processing algorithms increase the capabilities of optical sensors. To take full advantage of modern optical systems coupled with fast cameras, high efficiency robotic mounts are needed. The increasing number of satellites in LEOs, mostly due to deployment of megaconstellations, will redefine the population structure of space objects. It is envisaged currently that the Starlink megaconstellation itself will comprise nearly 12,000 objects.
(McDowell 2020) and SpaceX will not be the only one launch their satellites in orbit. Collision mitigations measures (Reiland et al. 2020) will reduce the risk of space-debris production but will require precise orbital information. High quality ground-based observations are therefore very needed. Due to the fact that objects on LEOs are visible only shortly after and shortly before sunset, the higher efficiency (dynamics) of the mounts, the more data can be acquired in the limited time available for observations.

Space traffic management and space safety are not the only areas of application of a fast and precise robotic mount. At the eve of the night-sky flooding by mega-constellations the astronomical community is very concerned how severe will this technological development interfere with purely astronomical ground-based observations. All areas will be affected, but for survey-oriented observations, typically carried out in a fully automatic manner, it will be a considerable challenge. A highly capable, direct-drive mount, coupled with modern optical systems and detectors will allow one to increase responsiveness, robustness and therefore directly impact the astronomical community.

In this paper we have described the process of designing and commissioning an optical sensor dedicated to SSA applications. The sensor has been designed with sidereal and non-sidereal tracking capabilities in mind and focused on high precision and very high dynamic range. We have shown that it is possible to track objects on LEOs with an rms of 1–3 arcseconds during an entire visible pass. At the same time the access to the entire stack of the control system—from position measurement, via drive control, to high level software—it is possible to tune the system’s parameters to achieve highest possible dynamics. At the same time, access to the full stack provides interesting research capabilities in the control theory and signal acquisition areas. In the following years megaconstellations are expected increase the number of space objects by tens of thousands. This will cause an increase of collision avoidance manoeuvres. The possibility to acquire high quality data in a very short time will be of utmost importance. The system described in this paper fulfils current requirements of ground-based optical stations and is well suited for further development.

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