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Development of active optics for thin meniscus mirror in 1-meter-class telescopes

Christian Schwaer, Andreas Sinn, and Georg Schitter

Automation and Control Institute (ACIN), TU Wien, Gusshausstr. 27-29, Wien, Austria

ABSTRACT

This paper presents the ongoing project of implementing an active optics system in an 1-meter telescope to build a lightweight, cost-effective system with high imaging quality. A systematic design methodology for meniscus mirrors based on thin plate theory and finite element analysis enables target-oriented engineering of a support system that takes the application-dependent optical mirror requirements into account. The actuators for the lateral and axial system are based on stepper motors and designed in a modular manner, adjustable for a wide range of nominal force values. The axial actuators integrate an optical force measurement to achieve a compact design. Laser triangulation sensors placed in the mirror cell measure the lateral mirror position in 3 degrees of freedom with respect to its cell, providing position data that is used in a feedback control to compensate for finite stiffness of the support structure and thermal disturbances. Tests of the lateral system's performance show maximum displacements of 1.4 µm in both lateral directions, keeping the according wavefront RMS error below 5 nm.

Keywords: Active Optics, Telescope, Meniscus Mirror, Mechatronic System Design

1. INTRODUCTION

Telescopes with primary mirror diameters in the meter-class are used in applications such as astronomy,[1] optical satellite communication,[2] satellite laser ranging[3] and observation of space debris.[4] The increasing demand of telescope systems together with the high effort for building large observatories necessitate the development of autonomous telescopes for remote operation with robustness regarding environmental influences to mitigate complex surrounding infrastructure. Additionally, a small system mass, obtained by a lightweight primary mirror, achieves ease of transportation and cost-effectiveness of the telescope system.

In order to increase the robustness with respect to environmental influences and to allow the reduction of mirror mass while maintaining the aperture size, an active optics system is employed in large astronomical telescopes. It was first described for the New Technology Telescope (NTT) of the ESO.[5] This approach of an active support structure, especially for the primary mirror, allows a large reduction of mirror mass since actuators at the mirror's back are able to compensate for angle-dependent gravitational deflection of the thinner and more flexible mirror. The smaller thickness leads to a lower thermal time constant, thus decreasing temperature dependent image quality degradation. Additionally, time, energy and cost of mirror production are decreased significantly because less low thermal expansion material is consumed. Also, the requirements regarding surface shape after polishing are eased since the manufacturing error can be actively compensated.[6] Furthermore, the effort of maintaining the telescope is greatly decreased since it can use the implemented sensors and actuators to maintain itself.[5]

Several telescopes in the 8 m diameter range implemented active optics after its invention, e.g. the 8.2 m Very Large Telescope (VLT),[7] the 8.0 m Gemini Telescope[8] and the 8.2 m Subaru telescope.[9] Telescopes in the 4 m range with active optics systems are the 4.1 m Visible and Infrared Survey Telescope for Astronomy (VISTA),[10] the 4.3 m Discovery Channel Telescope (DCT),[11] the 4.0 m Eastern Anatolia Observatory (DAG)[12] and the 4.2 m Daniel K. Inouye Solar Telescope (DKIST), formerly known as Advanced Technology Solar Telescope (ATST).[13]

Corresponding author: Christian Schwaer
E-mail: schwaer@acin.tuwien.ac.at, Telephone: +43 1 588 01 376 522

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Only few telescopes with less than 4 m primary mirror diameter implement active optics, e.g. the 2.6 m VLT Survey Telescope (VST)[14] and the 2.1 m San Pedro Martir telescope.[15]

To make an active optics system feasible for smaller telescopes and new applications such as satellite communication and space debris observation, the concepts used in the existing systems have to be adapted. First, the systems are usually single-unit productions, designed explicitly for one specific mirror. If an active support system is to be implemented as a standard for telescopes in the meter-class for various applications, a general approach is necessary to efficiently design the mirror support dependent on application-specific requirements. Second, the actuators used in the axial support, which apply a force distribution to the mirror in order to compensate occurring deformations, are either pneumatic with force sensing by pressure measurement[10,12] or electromechanic with force measurement by strain gauge sensors.[11,14] This leads to the need for an extra compressor and connecting hoses or a bulky and expensive force sensor. Also, in case of pneumatic actuators the adaptability with respect to a variety of nominal forces is restricted, but necessary when used in telescopes with different mirror geometries. electromechanical actuators often use expensive components such as ball screws and harmonic drives.[11] Third, the mechanical fixed points for defining the position in lateral direction, as used in all active optics systems, require tedious manual alignment and exert mirror-deforming forces under thermal expansion.

The main contribution of this paper is the systemic analysis and implementation an active optics system for a 1-m meniscus mirror which mitigates the mentioned challenges. A general methodology is developed to design an active support system for meniscus mirrors while taking application-dependent requirements into account. A modular, electromechanical actuator using commercial off-the-shelf (COTS) components with integrated optical force sensing to achieve a compact actuator-sensor-unit for the axial support is presented. For the lateral positioning of the mirror, laser triangulation sensors are integrated which measure the mirror position in 3 degrees of freedom (DOFs) with respect to its cell. This data is used in feedback control to provide virtual fixed points. The utilized lateral actuators are based on the same principle as the axial actuators, with an adaptation to transfer tensile forces, also.

The paper is organized as follows. Sec. 2 provides a description of the design methodology for the support of a primary meniscus mirror. The actuation principle with an integrated optical force sensor for the axial actuators is presented in Sec. 3. In Sec. 4 the lateral support system for the mirror is investigated. Finally, the conclusion and outlook are provided in Sec. 5.

2. DESIGN METHODOLOGY

The active optics systems developed until now are mostly single-unit productions for large astronomical observatories. Due to the utilization of telescope systems in several new applications, a general methodology to design the support system with respect to application-dependent requirements is necessary. This section therefore presents a guideline for the engineering design of an active optics system for the application in telescopes of the meter-class. An extensive description of this methodology is presented in Ref. 16.

2.1 Active support design

At the beginning of the design procedure, the mirror diameter and the optical requirements on the system are obtained, depending on the application and more specifically the properties such as desired light gathering power, optical resolution or data rate. When an initial mirror thickness and material is set, the algorithm shown in Fig. 1 can be applied.

First, thin plate theory is used to analytically obtain the necessary number and radii of concentric support rings in which the axial actuators are going to be placed. The result is used as initial condition to keep the computational effort of the subsequent finite element analysis (FEA) to optimize the ring radii and the weight fraction taken by each ring small. Following the degradation relation for meniscus mirrors when the continuous ring support is replaced by a discrete point support,[16] the design can then be discretized, obtaining the number of actuators per support ring and their nominal force values when the system is pointing to zenith, finalizing the axial support design.

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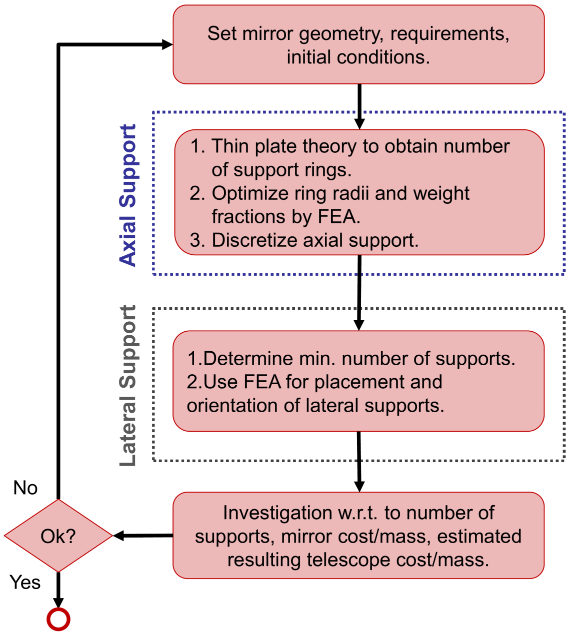

Figure 1: Flowchart of the proposed methodology for designing an active optics support.

A FEA is used for the lateral support, also. The initial number of equidistant actuators is selected such that the stress introduced to the mirror by the lateral forces is comfortably below the tensile and compression strength of the material. Then, a first optimization is executed to find the parameter β, which describes the ratio of tangential force to the total force[17] and therefore, the force vector at the support points. Using this result the number of actuators is increased until the requirements are met.

In a last step, the obtained support is investigated regarding number of supports, mirror and telescope mass as well as costs of the whole system. If the result is not satisfactory, the algorithm starts from the beginning. Since the results of the analytical solution together with the discretization degradation give a sophisticated estimation of the final result, it is easy to evaluate the effects of the adaptation of the mirror geometry, thus allowing an efficient engineering process.

2.2 Results for a 1-m Telescope

The presented approach is utilized to design the active optics system of a Ritchey-Chrétien f/6 telescope with Nasmyth focus and a primary mirror diameter of 1 m. The complete mirror geometry data including material parameters of borosilicate glass are shown in Table 1. For the axial support, a total number of 32 actuators in 3 concentric rings with 6, 11 and 15 actuators per ring is obtained. The lateral support consists of 8 actuators with angular distance of 45° and $\beta = 0.704$. For a description of the design value β please see Refs. 16, 17. The deformations of the mirror induced by this support when pointing to zenith and horizon are shown in Fig. 2(a) and Fig. 2(b), respectively. Fig. 2(b) also shows the lateral force application locations as well as their orientation. The RMS error when pointing to zenith, i.e. the axial support takes the whole weight of the mirror, is 8.7 nm, the one when pointing to horizon is 2.3 nm. The peak-to-valley (PV) errors are 42.4 nm and 40.5 nm, respectively.

3. ACUTATOR-SENSOR UNIT

Deformations of the mirror shape are corrected by using the axial actuators to apply a force distribution to the mirror. Due to the missing adaptability of pneumatic actuators, a modular electromechanic actuator is

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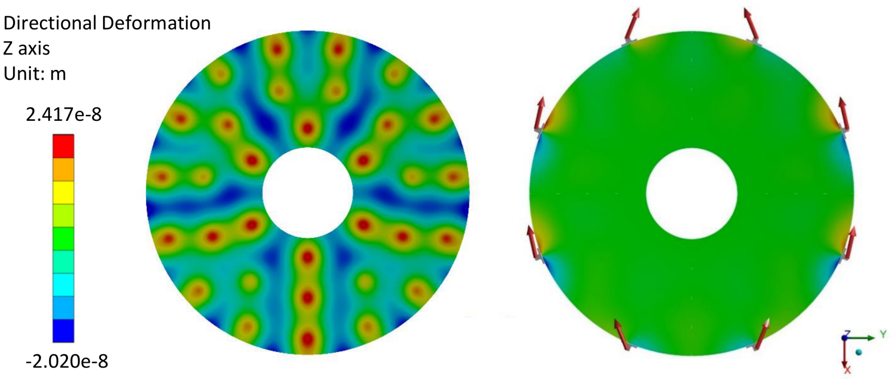
Table 1: Material parameters of borosilicate glass and mirror properties.

Parameter	Symbol	Value	Unit
Density	ρ	2.23	$\mathrm{g \cdot cm^{-3}}$
Young's modulus	E	63	GPa
Thermal expansion	α	$3.3 \cdot 10^{-6}$	$\mathrm{K^{-1}}$
Poisson's ratio	ν	0.20	–
Mass	m	40.35	kg
Outer diameter	D	1.0	m
Hole diameter	d_h	0.28	m
Thickness	h	0.025	m
Radius of curvature	R_C	4.0	m



(a) (b)

Figure 2: Design results for the primary mirror active optics system. (a) Axial system with 32 supports in three rings. The RMS and PV surface errors are 8.7 nm and 42.4 nm, respectively. (b) Lateral support system with 8 actuators and $\beta = 0.704$. The RMS and PV errors when pointing to horizon are 2.3 nm and 40.5 nm, respectively.

developed. In order to replace bulky and expensive strain gauge sensors, a sensor based on optical distance measurement is designed for seamless integration into the actuator to achieve a compact actuator-sensor-unit with precise force measurement.

3.1 Actuator system

A cross-sectional view of the electromechanical actuator, based on a stepper motor with gearbox, is shown in Fig. 3(a). The rotary motion is transmitted to a trapezoidal screw by an Oldham-style coupling which accounts for radial, axial and angular misalignments. The trapezoidal screw transforms the rotation into a translation by an according nut attached to a linearly guided component. In order to achieve the necessary force resolution of 5 mN,[16] an arrangement of six compliant helical springs transfers the translational movement to a force on the mirror's back.

The actuator for this project is a push-only device with a range of 0 N to approximately 24 N. This is sufficient for alt-azimuth telescopes with an operating range between 15° and 90° elevation. The force range and resolution can be easily adapted by replacing the springs accordingly, thus achieving a modular design of the actuator. In order to coordinate all the actuators of the active optics system, every actuator is equipped with a STM32-based microcontroller with Controller Area Network (CAN) connection.

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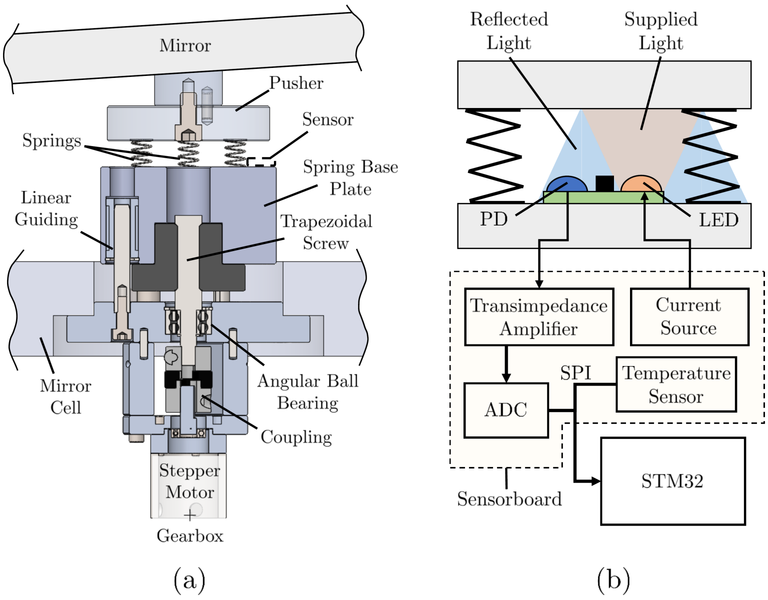

Figure 3: (a) Cross-section view of the electromechanical axial actuator with spring arrangement to achieve desired range and resolution. (b) Optical force sensor based on LED and PD on a compact PCB for seamless integration into the actuator.

3.2 Optical force sensor

Due to the spring arrangement in the actuator with frictionless relative movement between spring base plate and pusher, the force applied to the mirror only depends on the measured distance between these components. The integrated sensor is based on an optical proximity sensor which consist of a light emitting diode (LED) and a receiving photodiode (PD) where infrared light is emitted by the LED and reflected by a target. The reflected light leads to a current in the PD depending on the incoming light intensity,[18] see Fig. 3(b).

The current arising from the reflected light at the PD is processed by a transimpedance amplifier in photovoltaic mode which converts the current into an according voltage. This voltage is then digitized by a 16-bit analog-do-digital converter (ADC) which sends the acquired data to a microcontroller over the serial peripheral interface (SPI). In order to determine and potentially compensate temperature-dependent influences on the measurement result, a temperature sensor is placed on the PCB also. For the detection of tilting motion between the base plate and the pusher which leads to a distance and therefore force difference, while the true force might be unchanged, a total of three optical sensors are integrated into every actuator.

3.3 Validation

For the performance evaluation of the optical force sensor, an actuator with three optical sensors implemented as described above is compared to a commercial, calibrated force sensor based on strain gauges (KD40s, ME Messsysteme, 20 N nominal force) and an interferometer used as reference measurement. Since the mirror as target for the interferometer is mounted on the guided spring base plate, a tilting motion of this component with respect to the interferometer sensor head is avoided.

After calibration and determining the temperature compensation for the optical sensors, the precision of the optical sensor is compared to the interferometer at arbitrary points within the sensor range. Therefore, the mean value of the three distances is calculated and compared to the distance obtained by the interferometer measurement as shown in Fig. 4(b).[18] The RMS error of the mean value to the interferometer distance measurement

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calculates to 0.85 µm. For small distances, i.e. where the characteristic curves of the optical sensors approach their peaks, a slight degradation of the accuracy is visible. However, the accuracy is still in an acceptable range and this region coincides with the smallest actuator forces at very low elevation angles. This distance error can also be expressed with respect to the force due to known spring stiffness. The RMS error of the optical sensor is 4.5 mN, i.e. approximately 0.02% of the full range.

In Fig. 4(c), the force values of the two force sensors are depicted as difference to the reference. The strain gauge force sensor achieves an RMS error of 11.2 mN, i.e. the proposed sensor exceeds the performance of the strain gauge sensor by a factor of 2.5. There is a correlation between the two force sensors with respect to the reference visible, i.e. small effects in the mechanical structure between the pusher and the top support structure appear to influence the force measurements but not the interferometer measurement. Considering the standard deviation as well as the precision specified by the manufacturer of the strain gauge force sensor,[18] the comparison is assumed to be valid.

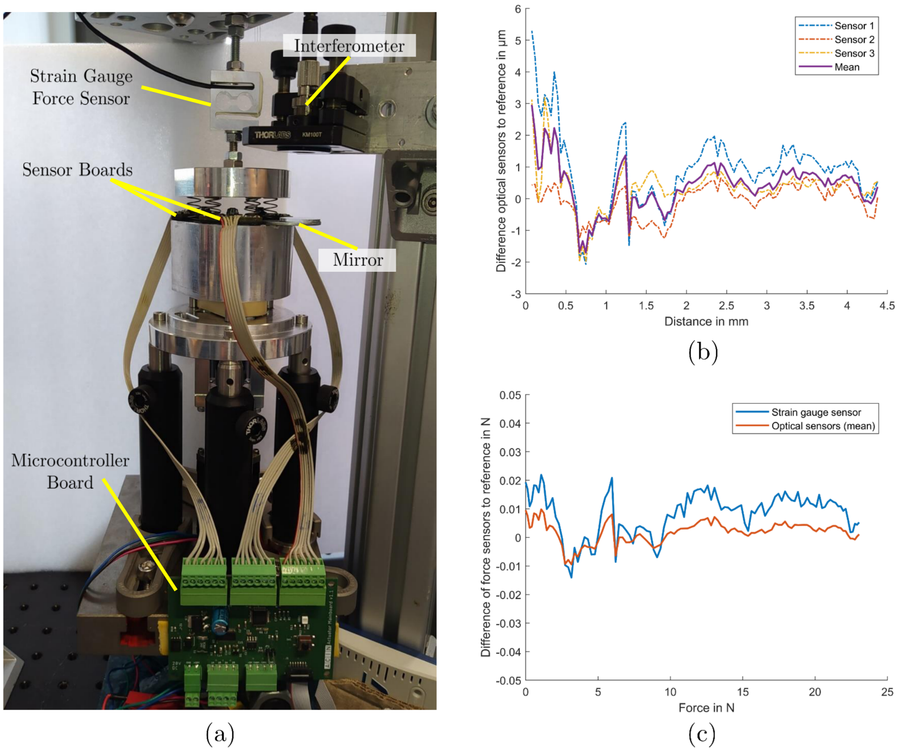

Figure 4: (a) Validation setup with commercial strain gauge sensor and independent reference interferometer measurement. (b) Deviation of the measured distance of optical sensors compared to the interferometer. The RMS error of the mean value of the three optical sensors is 0.85 µm. (c) Force difference between optical and strain gauge force sensor to interferometer. The RMS error of the optical sensor is 4.5 mN, the one for the strain gauge sensor is 11.2 mN.

4. LATERAL SUPPORT SYSTEM

For testing in the laboratory during the development of the active optics system an aluminum mirror is used. Aluminum has similar mechanical properties compared to borosilicate glass but is easier to manufacture, less

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sensitive with respect to shocks and scratches and therefore better suited. The aluminum mirror with its lateral support is embedded in a mirror cell that is rotatable in the elevation axis, see Fig. 5. The laser triangulation sensors are used to obtain the mirror position in 3 DOFs, x, y and Φ respectively. An implemented feedback control for the mirror position provides virtual lateral fixed points which ease the alignment process and do not exert distorting forces on the mirror under thermal influence in comparison to the usual mechanical fixed points.

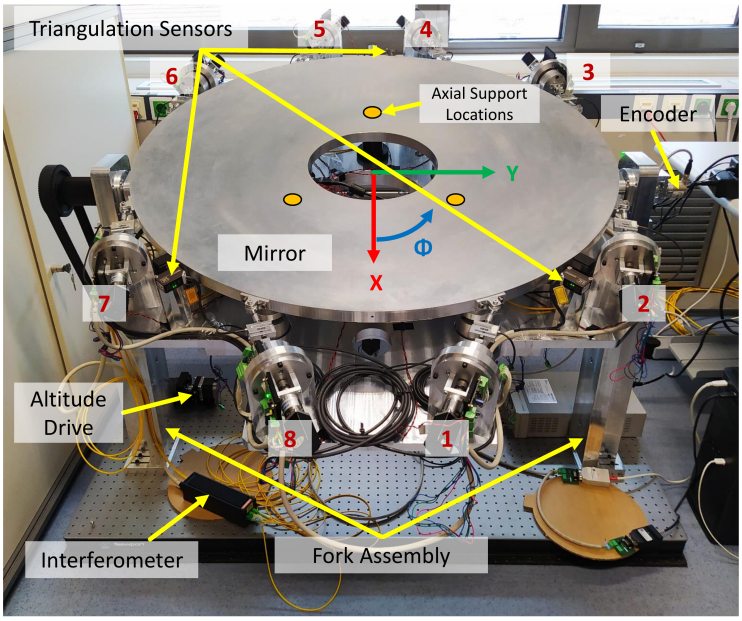

Figure 5: Laboratory setup with aluminum mirror, slewable in elevation axis. Three laser triangulation sensors determine the mirror's position with respect to its cell in 3 DOFs. The 8 lateral actuators are placed at the mirror's circumference.

4.1 Lateral actuator

The lateral actuator is based on the actuation principle presented in Sec. 3, adapted to also take large tensile forces, however. The link between actuator and mirror consists of a frictionless flex pivot bearing, commercial strain gauge force sensor and ball joint as shown in Fig. 6. The custom made readout electronic acquires the analog signal of the Wheatstone bridge which is formed by the strain gauges. After conversion with an analog-to-digital converter (ADC), the digitized data is sent to the microcontroller board where the force feedback control loop is implemented. The microcontroller receives setpoints from the host over the CAN bus.

4.2 Lateral control system

For controlling the position of the mirror, a cascaded control loop with local force feedback is implemented, see Fig. 7. The internal control loop which is running on every actuator has a closed-loop bandwidth of at least 3 Hz as shown in Ref. 19. The measurement data of the triangulation sensors is used in the outer loop to maintain mirror position under disturbances applied to the system such as wind, temperature and elevation changes. The sensors together with the feedback control thus act as virtual fixed points of the mirror. Due to small crosstalk between the x- and y-axis, two separate SISO-PI-controllers are utilized to control these axes. Deviations in the Φ-axis do not affect imaging quality, but this rotational freedom has to be controlled nevertheless since large deviations would cause the actuators to reach their end of range. Thus, a PI-controller with much smaller

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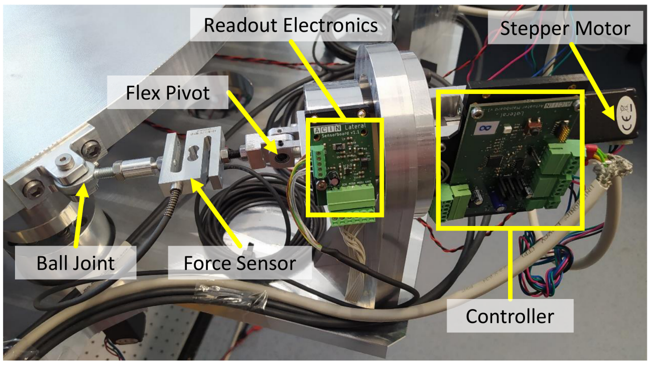

Figure 6: Lateral actuator with ball joint, flex pivot and commercial strain gauge force sensor.

bandwidth than for the translational DOFs is implemented.[19] The controllers are running on a host system which sends the force setpoints for every actuator over the CAN bus.

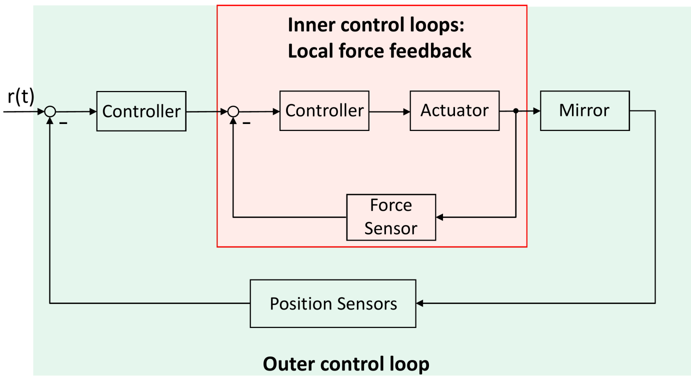

Figure 7: Cascaded control loop with local force feedback on every lateral actuator and position feedback in the outer loop.

4.3 Results for lateral support system

In order to evaluate the performance of the position control loop, a disturbance in form of changing elevation angles from 3° to 78° is applied to the system, see Fig. 8(a). This elevation slew with a speed of 0.2 deg/s is executed twice, first without control and afterwards with control turned on. It is required that the maximum combined displacement of both translational axes is below 10 µm in order to keep the resulting wavefront error below 5 nm.[19]

The resulting displacements of the mirror due to the slewing are shown in Fig. 8(b). The maximum displacements for the passive system are 241 µm and 101 µm in x and y, respectively, while the RMS errors are 140 µm and 53 µm, thus far exceeding the requirement. For the controlled system, the maximum magnitude of the combined x and y displacements is 1.4 µm with 0.33 µm RMS, therefore meeting the requirement of less than 10 µm comfortably. The angular displacement is reduced from 12.6 µrad to 5.1 µrad. Furthermore, due to the virtual fixed points the alignment process is simplified since the mirror can be positioned without manually

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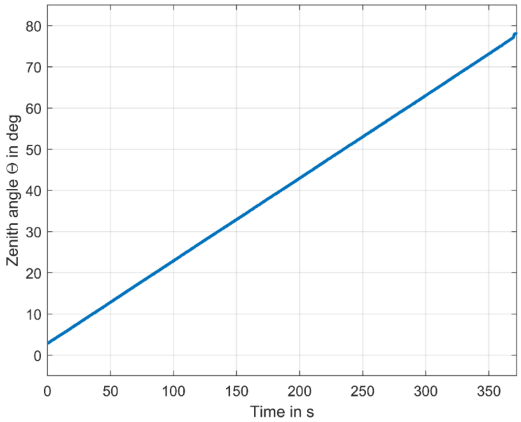
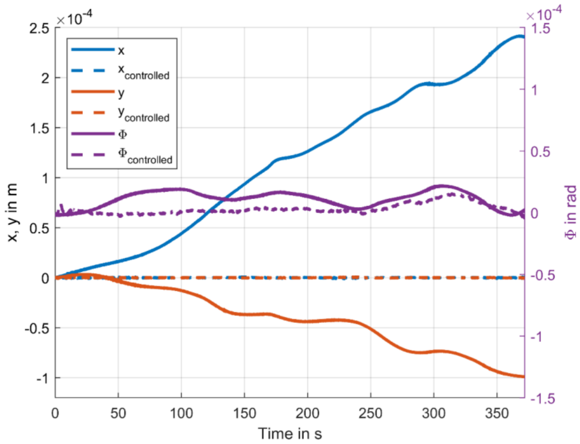
aligning the mechanical fixed points. Also, an operation under thermal influence is possible without negatively affecting the mirror surface.



(a)



(b)

Figure 8: (a) Zenith angle obtained by the absolute encoder over time during slewing. (b) Displacements of the mirror in 3 DOFs without (solid lines) and with (dashed lines) control.[19]

In summary, the systematic methodology to design an active optics support, the modular actuator with precise optical force measurement and the lateral positioning system, which is able to maintain the mirror position with a factor of 7 below the requirement of 10 µm, demonstrate the progress towards the implementation of an active optics system for meter-class primary mirrors.

5. CONCLUSION

In this paper, the design and implementation of an active optics system for a telescope system with a primary mirror diameter of 1 m is presented. In order to efficiently design an application-oriented support structure, a general approach to design meniscus mirror supports is developed and utilized for the targeted system, leading to a system with 32 axial and 8 lateral supports for the 1 m mirror. Furthermore, a compact actuator-sensor-unit with integrated optical force sensor is developed and achieves the required accuracy in the range of 5 mN compared to an independent interferometric reference measurement. The inherent modularity of the actuator allows to scale it for application in larger telescopes. For the lateral positioning of the mirror, laser triangulation sensors are integrated into the mirror cell and their data is utilized in feedback control to provide virtual fixed points for the mirror. With control, the RMS error over the elevation angle is improved by factor 519 and 294 in both lateral directions, compared to the uncontrolled system.

Building on the obtained results, the axial subsystem is going to be implemented and the support will be investigated regarding its ability to compensate for mirror deformations.

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