Integrated Force Sensor based on Optical Distance Measurement for a Modular Actuator used in Active Optics

Christian Schwaer, David Stefanek, Andreas Sinn and Georg Schitter

***Abstract*— This paper presents a modular actuator with an integrated force sensor for the utilization in an active optics support system for primary mirrors in the meter-class. The actuator uses a commercial stepper motor together with an arrangement of helical springs. The force measurement of the individual actuators required for the active optical system is based on an optical proximity sensor which measures the distance between the components connected by the springs. This way, the force sensor is highly integrated into the actuator and for the developed system a precise force measurement with an RMS error of 4.5 mN over a range of 24 N is achieved.**

I. INTRODUCTION

Ground-based reflecting telescope systems are used since several centuries for observing the night sky [1]. In order to increase the resolution, the mirror's diameters also increased over time, yielding a point where the primary mirrors of the telescopes needed to be manufactured with large thickness to withstand gravitational deformation. This results in extremely heavy mirrors with large thermal inertia [2]. For this reason, the so-called active optics system was developed for the New Technology Telescope (NTT) of the European Southern Observatory (ESO) [3]. In active optics systems actuators, equipped with force sensors, are placed at the mirror's back to compensate for mirror deflections due to environmental influences such as gravity and temperature. Over the years, active optics systems have been implemented in newly built telescopes with primary mirror diameters larger than 2.6 m [4] [5] [6] [7], with only very few applied in smaller telescopes [8] [9]. Since the telescopes with primary mirror diameters of several meters are usually single-unit systems, the actuators were also developed for the requirements of the according telescope and the actuation principles range from hydraulic [10] over pneumatic [11] to electromechanic [12].

However, besides astronomical purposes, recently telescopes in a range from 0.6 m to 2 m are also used for other applications such as free-space optical satellite communication or space debris observation. Due to the increasing amount of space debris as well as for the creation of future optical ground station networks and telescope arrays, it is necessary to build much larger numbers of telescope systems [13]. It is essential that these systems are high-performing, robust to environmental influences with respect to possible placement at remote locations with minimal infrastructure and lightweight for ease of transportation and cost-effectiveness. Implementing active optics into these telescopes promises to combine high imaging quality with robustness and lightweight design. In order to use the actuator unit for varying mirror sizes and application-dependent imaging requirements it needs to be highly adaptable with precise force measurement due to the lightweight mirror design.

This paper therefore presents a modular actuator that can be utilized as unit in active optics systems. It is based on a stepper motor with planetary gear box, which enables a compact design and the drive unit is easily interchangeable. An arrangement of springs enables another adaptability of the actuator. Force measurement based on optical proximity sensors furthermore achieves a compact design between mirror cell and primary mirror. Section II, the actuator is presented in detail followed by a description of the sensor design in Section III. The experimental setup together with the validation results for the proposed actuator-sensor-unit are shown in Section IV. Section V finally concludes the paper.

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II. ACTUATOR

In order to design a suitable actuator for an active optics system, the requirements need to be obtained, which primarily depend on the mirror weight, its thickness and the number of utilized actuators. The prototype presented in this work is designed for a force range of 0 to around 24 N with a force resolution down to 5 mN, which is determined for the worst case scenario of astigmatic excitation [14]. For more realistic, random force distribution at the axial supports it is assumed that 20 mN are sufficient.

The cross-sectional view of the actuator is shown in Fig. 1. It consists of a stepper motor with a planetary gearbox, and the rotation is transformed into translation by an according nut, mounted to the spring base body which is guided by three linear ball bearings to prevent tilting. Over an arrangement of six helical springs in parallel which are far more compliant than all the other elements of the actuator, the force applied to the mirror can be easily adjusted. In this case, the actuator is a push-only device, which is sufficient for telescopes with alt-azimuth mount since the operating range is approximately between 15° and 90° altitude [15]. Please note that the mirror is depicted as flat in Fig. 1, although there is a small curvature in reality since the radius of curvature is 4 m for the 1 m mirror.

Two components of the actuator, the spring stiffness and the stepper with gearbox, are selected based on the applied force range and the required force resolution of the actuator.

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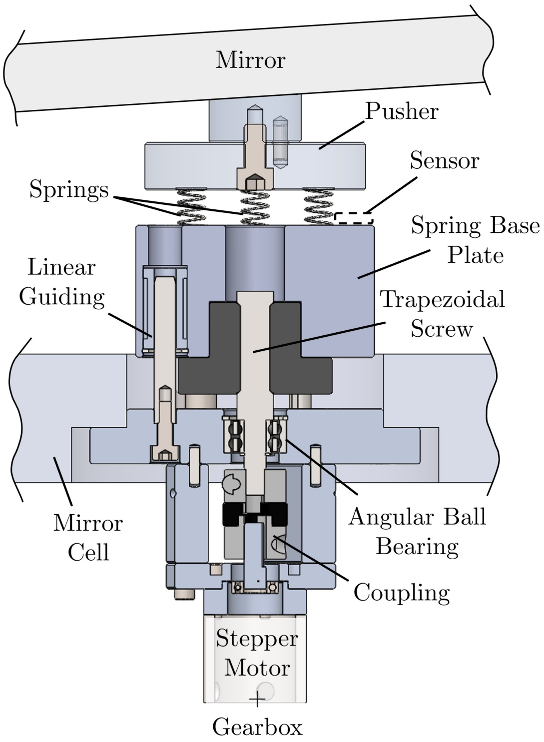

Fig. 1. Concept of the electromechanical actuator assembled into the mirror cell.

With a thread pitch of 2 mm of the trapezoidal screw, a spring constant of approximately 6 N/mm for the six parallel springs and a gearbox ratio of 14:1 lead to a force change of 4 mN per full step of the motor and a range of up to 30 N which coincides with the requirements.

The actuator is equipped with a control board based on a STM32 microcontroller which is concerned with collecting the data from the proximity sensor, process them and send the movement command to the stepper motor, i.e. it features a local force feedback loop. Additionally, the controller board has a controller area network (CAN) bus interface for the communication with a host system that implements the software for the complete active optics system. All the actuators in the axial support system receive force values from the host system which are then used as the desired values in the internal feedback control loop running on each actuator. Position sensors integrated into the mirror cell provide data for the outer control loop implemented on the host system for controlling the mirror position by changing the desired force values of the actuators.

Similar electromechanical actuators with spring arrangement have been built for the VST [15] and the DCT [16], where the latter also uses stepper motors, however with harmonic drive and a ball screw and constructed to also apply small pull forces. The benefit of the proposed actuator-sensor-system lies in the utilization of simple, commercial-off-the-shelf (COTS) components that are easily replaceable as well as the integrated sensor, see the following section, leading to a very compact design in axial direction.

It is noteworthy that this modular design introduces the possibility to utilize the actuator not only in the axial support of an active optics system, but also in an active lateral support where the actuators are located in the plane perpendicular to the optical axis [14].

III. Sensor

The concept of the actuator allows for a force measurement by obtaining the distance between spring base plate and pusher, i.e. parallel to the springs. Due to the spring arrangement and without guiding between these components, i.e. with frictionless relative movement, the force applied to the mirror only depends on the measured distance. The integrated sensor is based on optical proximity sensors 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, in this case the pusher. The reflected light leads to a current in the PD depending on the incoming light intensity.

In order to utilize this sensor principle, the LED and PD are used in one package (TCND5000, Vishay Semiconductors) which is placed on a printed circuit board (PCB). The LED is supplied with a current of 50 mA by a constant current source, see Fig. 2. The current arising from the reflected light at the PD is processed by the readout electronic circuit. A

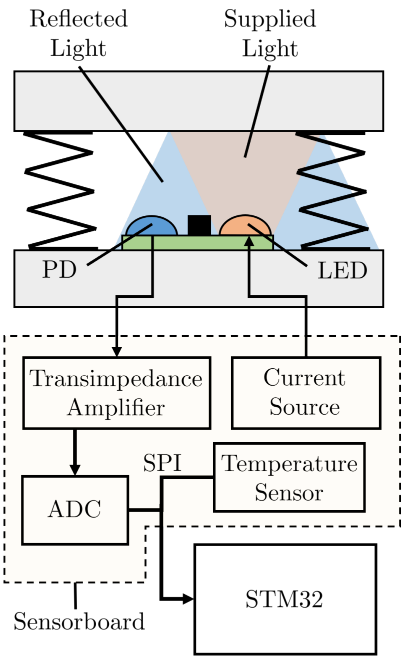

Fig. 2. Schematic of the sensor principle based on measured intensity of reflected light together with the implemented electronics on the sensor PCB and its interface to the STM32 microcontroller.

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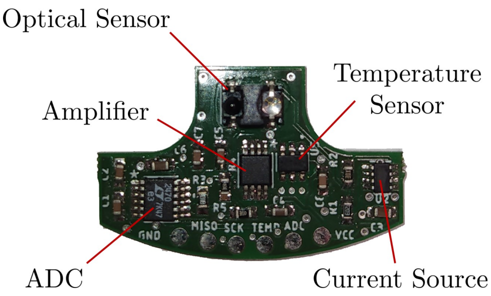

Fig. 3. Picture of the sensor board which can be integrated between the spring arrangement.

transimpedance amplifier in photovoltaic mode converts the current into an according voltage which is then digitized by a analog-to-digital converter (ADC). The 16-bit ADC (LTC2470, Analog Devices Inc.) is connected to the STM32 controller over a serial peripheral interface (SPI) and transmits 800 samples per second. Additionally, a temperature sensor is placed on the PCB to determine and potentially compensate for temperature-dependent influences on the measurement result.

A picture of the equipped sensor board is shown in Fig. 3. The shape of the PCB allows the smooth integration into the actuator right between the springs. Since there is no linear guiding between pusher and spring base body, a tilting motion between these two components can occur, leading to a change in the measured distance although the force applied to the mirror might be the same. For this reason, and to improve the general accuracy, three sensors are implemented for each actuator and placed at an angular distance of 120° with respect to each other. This way, three distance measurements are obtained to identify possible tilting and the arithmetic mean value is used for force measurement. Emerging lateral forces in the system are compensated by a separate lateral support system [14].

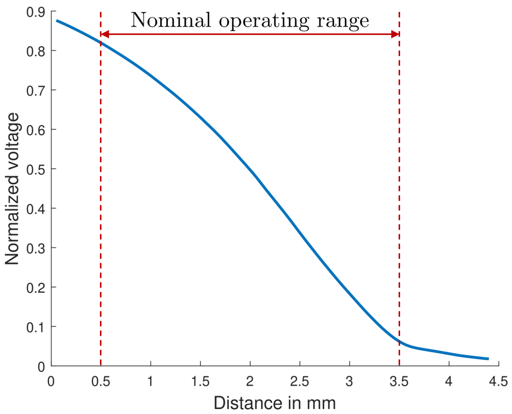

Fig. 4. A characteristic curve of a single optical proximity sensor.

The full characteristic curve of an optical proximity sensor is not monotonous. For distances close to zero between LED and target, the intensity is also zero. For increasing distance, the intensity also increases up to a point of peak intensity and then decreases again. For the case of this actuator setup, the first operating area between 0 mm and approximately 4.5 mm is used. The characteristic curve of normalized voltage over distance for this sensor is shown in Fig. 4. The voltage is normalized to the internal reference voltage of the ADC which is 1.25 V. The maximum normalized voltage is below 1 since the gain of the amplifier is selected such that the ADC input is always below its reference voltage to avoid saturation. Note the distance on the x-axis is measured from the bottom endpoint of the spring base plate upwards, i.e. at a distance of 4.5 mm the optical sensor is very close to the target which is why the voltage is almost zero.

IV. EXPERIMENTAL SETUP AND RESULTS

The setup which is used to evaluate the performance of the force sensor based on the optical distance measurement is

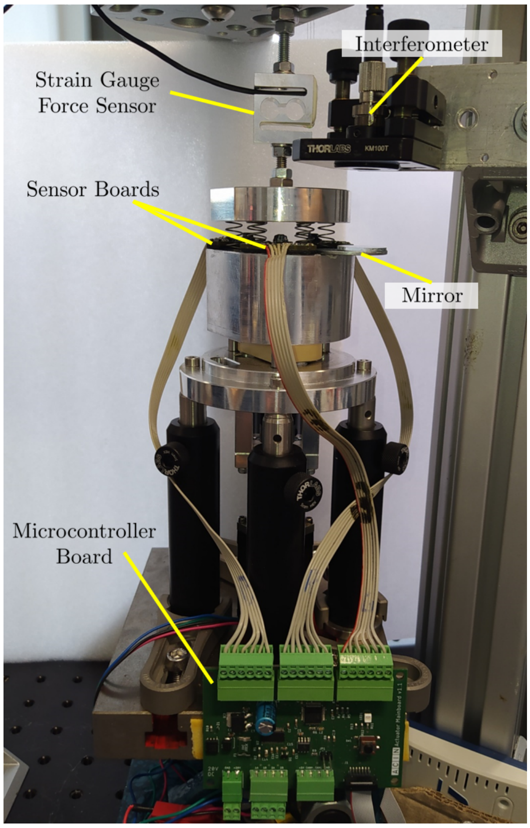

Fig. 5. Picture of the actuator with the integrated optical sensors. An interferometer is used as reference measurement and a commercial force sensor based on strain gauges for a statement about the actual forces applied by the actuator.

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shown in Fig. 5. It consists of the actuator with three optical force sensors implemented as described above. A commercial, calibrated force sensor based on strain gauges (KD40s, ME Messsysteme, 20 N nominal force) with a custom-made readout circuit is used to calibrate the force versus distance behavior. Since the optical force measurement exceeds the accuracy and precision of the strain gauge force sensor, an interferometer is 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.

A. *Calibration*

In order to characterize the optical sensor with respect to the force, a calibration process for the strain gauge sensor and the optical proximity sensors is executed as follows:

1) The strain gauge sensor is loaded consecutively with increasing reference masses from 0 kg to 2 kg and the voltage output of the readout electronic is recorded, which is one measurement cycle. This is done three times in a row to yield a mean voltage over force diagram for this sensor. The standard deviations for the different mass steps are shown in Table I.
2) The stepper motor drives the spring base plate in steps of about 40 µm, measured by the interferometer, from the beginning to the end of the range of the optical sensor while the output voltages of both, the optical sensor and the strain gauge sensor are recorded. This is done ten times and the mean value is calculated. For the optical sensor, this leads to a characteristic curve as shown in Fig. 4. For the strain gauge sensor, the result is a linear characteristic curve as expected for this sensor principle.
3) The obtained curves from Step 1) and 2) for the strain gauge sensor are combined to a force over distance diagram in order to determine a very precise force for a given distance measurement of the interferometer.

With the relation obtained in Step 3), the interferometer can be used as reference to compare it with the force determined by the optical proximity sensor.

B. *Temperature influence*

When investigating the curves for the optical sensor obtained in step 2 of the calibration process, a temperature influence on the measured voltage of the optical sensor can be observed since the voltage tends to decrease with increasing temperature as shown for ten consecutive measurement cycles in Fig. 6. In Fig. 6(a) the differences for every measurement

TABLE I
STANDARD DEVIATIONS OF STRAIN GAUGE FORCE SENSOR

Mass in kg	0	0.2	0.5	1	2
σ in µV/V	11.7	91.2	269	586	569
σ in mN	0.9	7	21	46	37

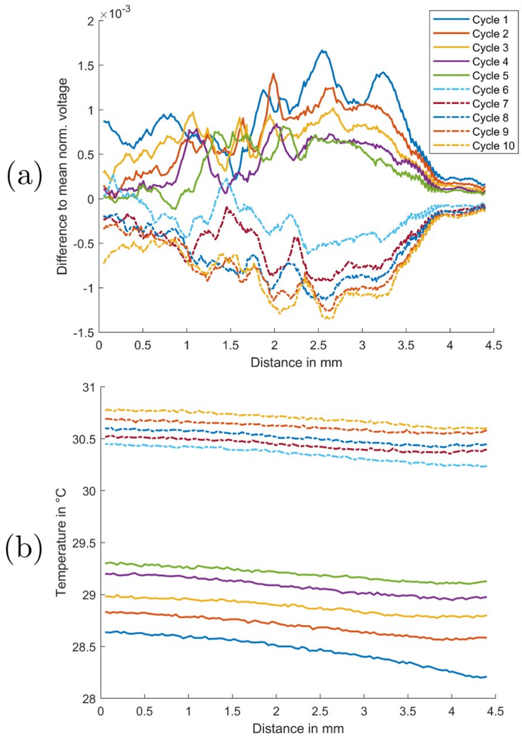

Fig. 6. Ten characteristic curves of one optical sensor are acquired consecutively with a pause after the first five curves to let the setup heat up. (a) Shows the differences of the (normalized) voltage output of the ten characteristic curves to their mean value (Fig. 4). (b) According temperature profiles for the ten measurement cycles, which clearly indicate a temperature rise after every cycle.

cycle to the mean of the ten cycles are depicted. With a nominal sensitivity of about 0.3 V/V/mm, a deviation of $1.5{\cdot}10^{-3}$ V/V (cycle 1) results in 5 µm measurement error for a temperature difference of 1.3 K. The according temperature profiles are shown in Fig. 6(b). However, for the same temperature difference, the influence also depends on the distance. For this reason, a correction factor with two inputs, temperature and distance, is implemented in order to describe the temperature dependency of the sensor system (optical sensor, readout electronics, temperature expansion of the PCB). It is approximated by a third degree polynomial in temperature and a second degree polynomial in distance, leading to a surface in 3D space as shown in Fig. 7 for a temperature difference of up to 2.5 K. The temperature range during operation in the telescope depends on the geographical location of the telescope system, daytime operation and if it is placed within a dome. It might reach up to 10 K, the proposed compensation can be extended to the desired temperature range, however. Due to the small length of the springs, their temperature expansion is neglected.

Of course, during operation without the interferometer,

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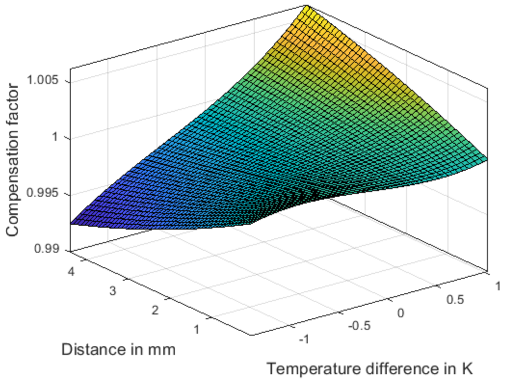

Fig. 7. Plot of the surface fit for the compensation coefficient.

when the voltage of the optical sensors is acquired, due to the temperature influence on the voltage there is an error in the distance measurement used as input for the compensation coefficient. However, since this error is in the range of micrometers, it is negligible compared to the full range of 4.5 mm and the small gradient of the coefficient.

C. Results

After calibration and determining the temperature compensation for the optical sensors, the precision of the optical sensor is compared to the interferometer. The actuator is driven to arbitrary locations within the measurement range where for each of the three optical sensors the distance is determined by using their characteristic curves and the according temperature compensation coefficient obtained in the calibration process. Then, the mean value of the three distances is calculated and compared to the distance obtained by the interferometer measurement. Figure 8(a) shows the measurement error between the interferometer and the optical proximity sensors over the whole range. The RMS error of the mean to the interferometer distance measurement calculates to $0.85\,\mu\mathrm{m}$. 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. Due to the force-distance curve obtained in Step 3) of the calibration process, this result can be expressed with respect to the force as shown in Fig. 8(b). The RMS error of the optical sensor is 4.5 mN, i.e. approximately 0.02% of the full range, which coincides with the requirement stated as worst case in SSection II. Also depicted is the strain gauge force sensor for comparison with an RMS error of 11.2 mN, i.e. the proposed sensor exceeds 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.

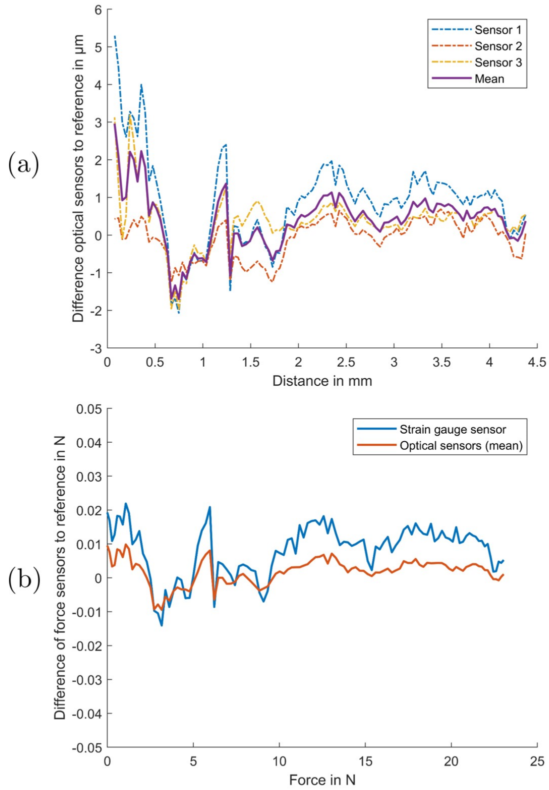

Fig. 8. (a) Differences of the obtained distances from the optical sensors to the reference measurement with the interferometer. (b) Difference of the optical sensors mean to the interferometer reference compared to the strain gauge force sensor.

Considering the standard deviation as well as the precision specified by the manufacturer of the strain gauge force sensor and the result shown in Fig. 8(b) the comparison is still assumed to be valid, however.

The results demonstrate that the proposed optical sensor concept is well suited for precise force measurements, thus enabling a compact, integrated and adaptable actuator for active optic mirror support systems.

V. CONCLUSION

In this paper, the actuation and force sensing principle for a system used in active optics of telescope mirrors is presented. A force measurement concept based on optical proximity sensors, that measure the intensity of reflected light from a target is proposed and used to determine the change of the springs' lengths. This design enables a seamless integration of three optical sensors into the actuator for higher precision. An experimental setup with interferometer measurement as reference and a commercial force sensor based on strain gauges is used to evaluate the proposed system. A force error of 4.5 mN RMS is achieved over an actuation range

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of 24 N, successfully demonstrating the potential of this approach and meeting the requirement to support a mirror for diffraction-limited performance. In addition, the utilization of a commercial stepper motor with gearbox and an arrangement of six helical springs between moving components of the actuator enables an adaptable system with respect to range of force and resolution.

Future work includes the evaluation of the presented system with respect to possible tilting motion between spring base plate and pusher as well as utilization in a primary mirror cell with active optics.

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