ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

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International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056230 · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296161

ELECTROMAGNETIC DEFORMABLE MIRROR FOR SPACE APPLICATIONS

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I. INTRODUCTION

To increase the collecting power and to improve the angular imaging resolution, space telescopes are evolving towards larger primary mirrors. The aerial density of the telescope mirrors needs to be kept low, however, to be compatible with the launch requirements. A light-weight (primary) mirror will introduce additional optical aberrations to the system. These may be caused by for instance manufacturing errors, gravity release and thermo-elastic effects. Active Optics (AO) is a key candidate technology to correct for the resultant wave front aberrations [1].

One important element in the adaptive optics correction chain is the deformable mirror, which corrects for the aberrations by manipulating the wave front. While deformable mirror technology for ground based applications is already widely available and reasonably mature, for space applications several development steps need to be made to comply with the different set of requirements. This is mostly due to the challenging environment, high reliability requirements, and the specific nature of the adaptive optics correction loop.

Several groups are working on deformable mirror technology for space applications. One example is the Actuated Hybrid Mirrors (AHM), which is a joint development of JPL, LLNL and Xinetics [2]. This deformable mirror technology is based on electrostrictive PMN type actuators on the back-side of the mirror.
The 'Unimorph deformable mirror for Space applications' has been developed by the University of Muenster, utilizing piezo-ceramic disks, oriented in a radial or key-stone pattern at the back of the mirror facesheet [3].
The mirror by CNRS-LAM [4] is a 24-actuator, 90-mm-diameter adaptive mirror which is based on piezo-ceramic actuators in a peripheral lay-out. The actuator lay-out is dedicated to deal with a low order and known set of Zernike modes.

Within the frame of an ESA research project (TRP), TNO is currently developing a deformable mirror (DM) designated to be used in an AO system on-board a future space mission, such as an earth observation satellite with a large monolithic primary mirror. The DM design supports relatively large apertures, such that the impact of field dependent wavefront errors is limited when using a single conjugate-plane wavefront corrector.
TNO's DM concept utilizes electromagnetic actuators which has several important advantages, such as high reliability, highly linear actuator response, and low power consumption. In order to verify the performance of the newly designed electromagnetic actuators, a prototype strip of three actuators has been built and tested, showing a highly linear actuator response. In this paper the design of the DM for space applications is further described, and the results of the actuator tests are presented.

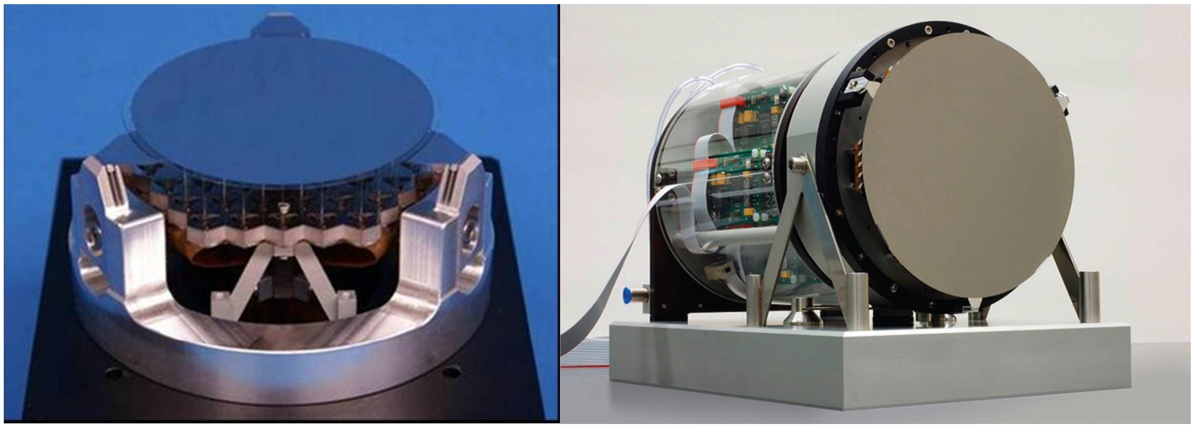

Fig. 1. First deformable mirror prototypes of TNO, containing 61 (left), and 427 actuators right [5].

II. DM TECHNOLOGY FOR SPACE APPLICATIONS

Over the last decade TNO, in collaboration with the technical universities of Eindhoven and Delft, developed a deformable mirror concept using electromagnetic actuators [5]. Two prototype mirrors have been built with 61 and 427 actuators in a hexagonal grid with 6.3mm pitch, as is shown in Figure 1. These prototypes have demonstrated the feasibility and potential of this electromagnetic actuated DM design. TNO is currently developing a new version of the DM actuators, which are based on the variable reluctance principle [6].

A. Renewed electromagnetic actuation principle

Fig. **2** shows a strip of three of the renewed electromagnetic actuators, designed for a minimal 18 mm actuator pitch. The actuator consists of a soft magnetic iron core which is press-fitted into aluminum housing. A lever with the moving plunger is cut out via wire EDM. The magnetic circuit is pre-energized via two permanent magnets, one above and one below the plunger. When the plunger is in the middle position, the forces from the two permanent magnets cancel each other out. The electromagnetic coil mounted at the lower end of the actuator generates an additional magnetic flux through the magnetic core which results in a net force on the plunger. The force on the plunger is transferred to the face sheet via a lever and a thin metal strut. The actuation principle is scalable for various actuator pitches, starting at about 4mm, and up to several centimeters.

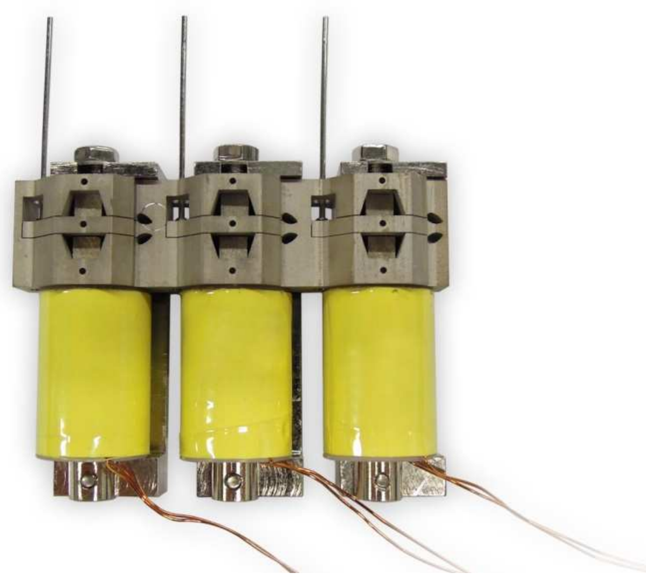

Fig. 2. A strip of 3 prototype electromagnetic actuators to be used in a deformable mirror. This strip enables a rectangular actuator grid with a minimal pitch of 18mm

To verify the actuator response, the strip of three prototype actuators is mounted in a test-rig in which each actuator is pushing against a lever, as shown in Fig. **3**. The stiffness of these levers is designed to be in the same order of magnitude as the stiffness of the face sheet. The stiffness of the lever and actuator are calibrated via a force probe. The motions of the levers are measured via a capacitive displacement sensor. Fig. **4** shows the measured force response of the 18mm pitch actuator to a current of ±300mA. As can be seen, the actuator shows an almost perfectly linear response up to the point that the magnetic core material starts to saturate. A linear region is selected between ±150mAmps, which corresponds to a force output of ±8N which is far sufficient to meet the required actuator strokes. The linearity over this range is measured to be within 99.5%. The motor constant is measured to be 52 N/Amps, which with a coil resistance of about 2.4Ω gives an actuator efficiency of $\alpha_{act} = 38N/\sqrt{W}$.

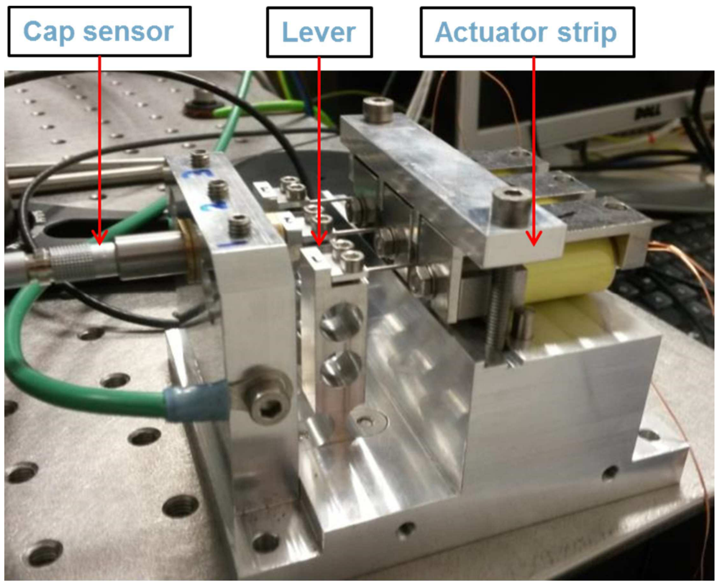

Fig. 3. Actuator test-rig. The actuators are pushing against a lever which stiffness is similar to the stiffness of the face sheet in the DM. The displacement of the lever is measured by a cap-sensor. The stiffness of the levers are calibrated via a force-probe

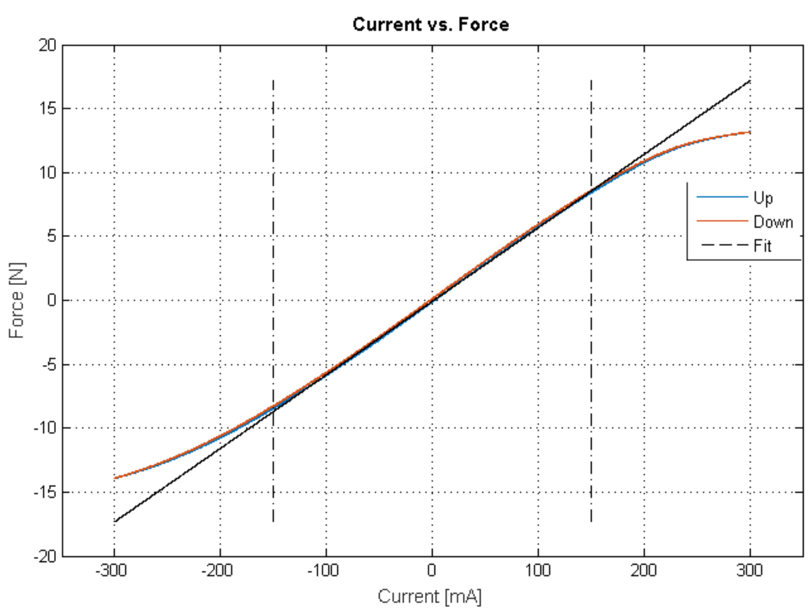

Fig. 4. Actuator force response for a ±300mA driving current (blue and red curve). The black solid line shows the linear fit over the ±150mA range over which the force output is ±8N. The linearity over this range is 99.5%, and the hysteresis is less than 1%.

B. Applicability for space applications

While the electromagnetic DM concept is developed for various adaptive optics applications, it has several key advantages which are making it highly suitable for space applications:

High reliability

The electromagnetic actuators are inherently highly reliability due to the lack of wear, aging or depolarization. On top of that, the drive electronics and actuator coils can be duplicated for redundancy without much impact on the overall systems complexity or mass. This redundancy on active components significantly increases the overall reliability and safety of the DM system, and is typically required for such active components in space applications. Furthermore, the actuator stiffness can be tuned to be relatively low which increases the actuator coupling in the DM response. Due to the high actuator coupling the neighboring actuators are capable of compensating for a failed actuator to a large extend, minimizing the impact of a potential actuator failure on the optical performance. This is as opposed to the relatively stiff piezoelectric actuators which lock the face sheet in case of failure.

Low drift

The update rate of the AO loop in space application is very slow as compared to most other AO applications due to the limited photon flux available for wave front sensing. Sampling period will range between seconds up to several months, depending on the application. The DM is required to maintain its shape in between the periods of the AO update rate within dozens of nanometers. This sets high requirements on the mechanical stability of the DM structure and the stability of the actuators.

Shape drift of the mirror can have many sources, such as thermal elastic behavior of the mechanics, electrical drift, or creeping behavior in the mechanics or actuation. Therefore, the full drift performance of a system should be quantified at system level in a relevant environment. However, the electromagnetic actuators facilitate a highly stable DM design due to the highly stable and constant force output of the actuators. This is due to the fact that the electromagnetic actuators do not suffer from creep behavior, as opposed to for instance piezo-electric actuators. Furthermore, these actuators allow for low complexity and statically determined mounting of the face sheet which minimizes potential drift due to thermal elastic behavior and potential stress releases and micro slip in the mechanics.

Linearity

Due to the slow update rate of the AO control loop, fast convergence of the AO loop is required in order to keep the up time as high as possible, and to effectively correct for slowly varying aberrations. This requires highly predictable and linear behavior of the actuators. As shown in Figure 4, the non-linearity of the electromagnetic actuators is very low (<0.5%) which enables fast convergence of the AO control loop.

Scalable to large aperture DM

Since the aim of adaptive optics in space applications is to correct for the aberrations mainly stemming from the M1 mirror, the DM will be optically conjugated to the M1 mirror. One important benefit of relatively large DM dimensions is the reduced anisoplanatic error, allowing for effective wave front corrections over larger fields of view with a single DM AO system. Furthermore, a sufficiently large DM does not require additional relay optics to project the M1 image on the DM which would otherwise reduce the throughput. TNO's electromagnetic DM concept is highly scalable starting from an actuator pitch of 4mm up to several centimeters. This scalability also allows high flexibility in the optical design to optimize the DM dimensions for optimal optical performance.

Low power dissipation

The power dissipation of the DM must be low since the available power on board the satellite is limited, and because heat dissipation on the DM may cause additional thermal drift of the optical system. The power dissipation of the electromagnetic actuators is very low due to the high actuator efficiency, and the fact that the inductive load of the coils can be driven by highly efficient Pulse Width Modulated Amplifiers. The total power dissipation for the 57 actuator DM depicted in Figure 6 is estimated around 5Watts of which only about 0.3Watts is dissipated in the actuators of the DM itself. Such low power dissipation fits well within the requirements for space applications.

III. DESIGN CASE FOR EARTH OBSERVATION

In the framework of an ESA TRP study, TNO is further developing the electromagnetic DM technology for both space science and earth observation applications. Fig. **5** and **Fig. 6** show an impression of a DM designed for space applications using 57 electromagnetic actuators. The dimensions used here are based on a 3.5m aperture earth observation telescope, in which the DM is the 5^{th} mirror in the optical layout at a position conjugated to the M1 mirror. In this configuration the DM is positioned on a 25^{0} angle with respect to the optical axis, such that the optical beam diameter on the DM is 430x475mm. The actuator grid is chosen larger than the optical pupil to provide sufficient mirror shape control at the boundaries of the optical pupil, resulting in an overall mirror size of an elliptical 610x670mm. The design is based on the identical actuators as shown in Fig. **2**, which are mounted on a supporting structure. The mirror membrane is 3mm thick and interfaced with the actuators via a whiffle tree structure to provide an even distribution of the actuator forces, and minimal gravity quilting during on ground testing. Based on the maximum actuator force levels and the mechanical stiffness within the system the achievable strokes of this DM are >20μm free stroke and >5μm inter actuator stroke.

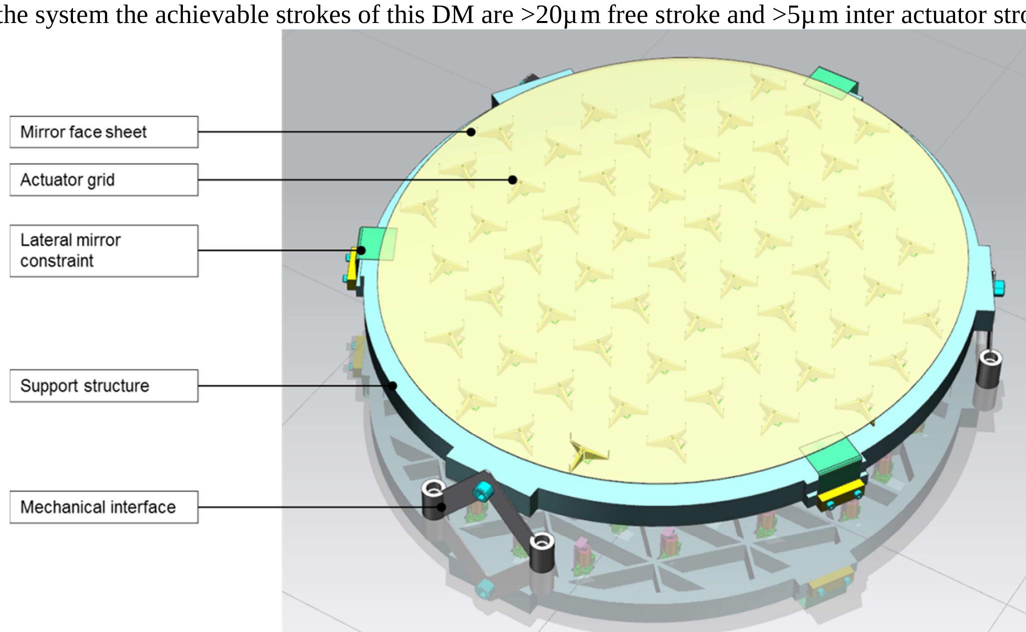

Fig. 5. Impression of the DM for space applications based on 57 electromagnetic actuators as shown in Figure 2. The mirror dimensions are an elliptical 610x670mm.

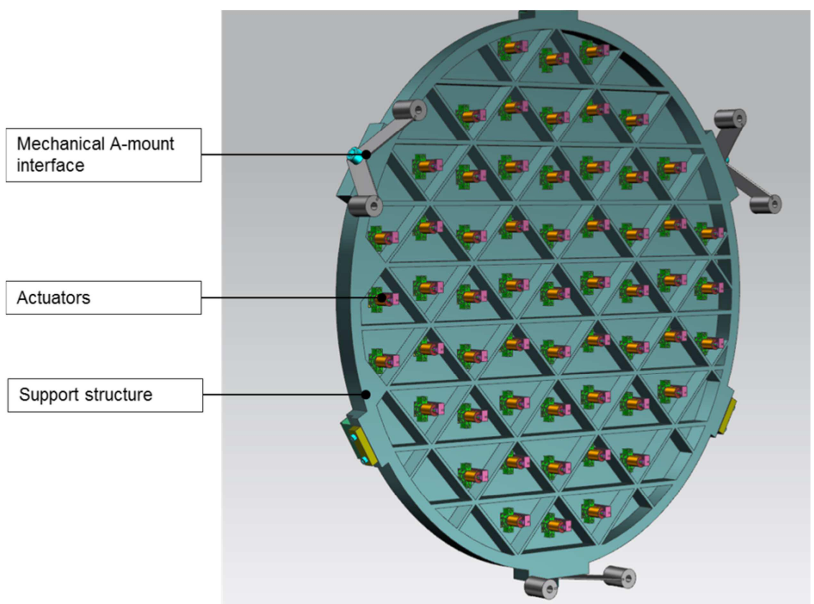

Fig. 6. Backside view of the DM for space applications.

IV. CONCLUSIONS &OUTLOOK

TNO is developing electromagnetically actuated deformable mirrors which are highly suited for space applications, due to their high reliability, high linearity and low drift. A renewed actuator concept is developed and tested with increased actuation efficiency in terms of power and volume. The DM concept is scalable to relatively large dimensions which are a particular advantage for space applications to minimize the impact of field dependent wave front errors when using a single conjugate-plane wave front corrector.

Within the frame work of the ESA TRP study, TNO is targeting to build a 57 actuator DM prototype based on the renewed actuator technology as depicted in Fig. **7**. This prototype design is a scaled down version of the DM depicted in Fig. **5** and Fig. **6**, with a mirror surface of Ø160mm. This prototype DM is designated for the adaptive optics correction chain demonstrator, which is aimed to demonstrate the potential of adaptive optics in space applications.

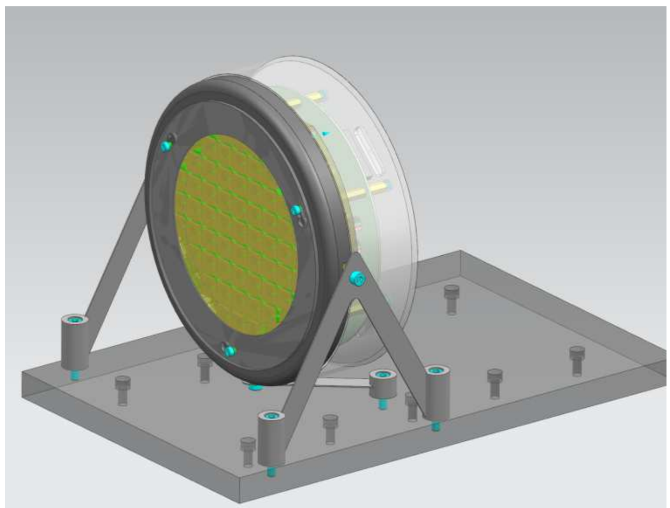

Fig. 7. Impression of the DM prototype designated for the adaptive optics correction chain breadboard.

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