Extremely high-resolution tip-tilt-piston mirror mechanism for the VLT-NAOS field selector

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ABSTRACT

NAOS (Nasmyth Adaptive Optics System) is the adaptive optics system presently developed for the ESO VLT. The field selectors are to feed the NAOS wavefront sensor with the light coming from an appropriate reference source which can be up to 1 arcmin (on the sky) distant from the center of the field of view. A large input tip-tilt-piston mirror selects the required part of the field of view. A second active mirror redirects the selected field to the wavefront sensor. The displacement of both mirrors are synchronized. The NAOS Field Selector consists of two extremely accurate tip-tilt-piston mirror mechanisms controlled in closed loop. Each mechanism provides a mechanical angle amplitude of ±6° with a resolution and mechanical stability of 0.42 arcsec rms over 20 minutes. This implies a dynamic range of 100'000 which requires an extremely accurate, very high resolution closed loop control. Both mirrors are made in SiC for low mass and inertia. The design configuration of the mechanism in based on three electromagnetic actuators 120° apart with the mobile magnets mounted on flexure guides. The mirror is supported by a combination of flex pivots and a membrane for flexibility in tilt and high radial stiffness. All kinematic joints consist of flexure elements so that the mechanism is essentially frictionless. The control system is implemented on a VME bus operated with the VxWorks OS with high electrical resolution (= 18-bit) A/D and D/A interface boards. The controller has been carefully designed to achieve the best overall performances, *i.e.*, a very good noise rejection, and a relatively low settling time.

Keywords: Tip, tilt, pointing, mechanism, field selector, adaptive optics, flexures, mirror

1. INTRODUCTION

In the framework of the Very Large Telescope (VLT) project, the European Southern Observatory (ESO) is procuring an advanced adaptive optics instrumentation called NAOS (Nasmyth Adaptive Optics System) with ONERA (France). Mounted at the Nasmyth focus of the telescope, NAOS holds an imaging instrument and rotates with the telescope Nasmyth adapter rotator.

The NAOS Field Selector (FS) mechanisms provide a tip-tilt movement of a flat, 90 mm diameter mirror for the adaptive optics of the ESO VLT. The mechanisms are designed to provide a mechanical angle amplitude of ±6°. The most challenging technical requirement is the demanded resolution of 0.42 arcsec which is also the mechanical stability value required over 20 minutes. The dynamic range of about 100'000 means a 17-bit accuracy end-to-end for the entire system.

The opto-mechanical design was largely inspired from previous CSEM projects such as PMLCT (Pointing Mechanism for Laser Communication Terminal) and FPM (Fine Pointing Mechanism for Silex Phase B) intended for space applications (Fig. 1). The configuration is based on three electromagnetic actuators 120° apart with the mobile magnets mounted on flexure guides. All kinematic joints consist of flexure elements so that the mechanism is essentially frictionless. The control system is implemented on a VME bus SBC operated with the VXWorks OS with high resolution (= 18-bit) AD and DA interface boards.

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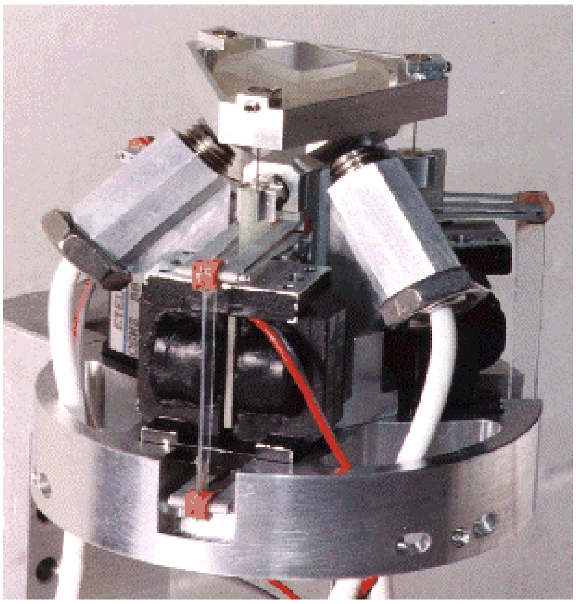

Fig. 1: Photograph of two-axis tilt fine-pointing assembly (PMLCT prototype)

2. FIELD SELECTOR SPECIFICATIONS

The two field selectors are identical and have been designed and built corresponding to the more stringent of the two specifications (Table 1), namely the 0.42 arcsec mechanical stability and the larger mirror diameter (85 mm as opposed to 25 mm).

Item	Specification
Tilt amplitude	±6°
Mechanical stability	0.42 arcsec rms
Mechanical resolution	0.62 arcsec
Rise time (for a 12° step)	2 sec (goal 1 sec)
Rise time (for a 0.24° step)	40 msec (goal 20 ms)
Mirror diameter	>85 mm
Mirror surface flatness	30 nm rms
Mirror surface roughness	20 Å rms
Mirror reflectivity	>97% from 0.45 to 1.0 µm >98% from 1.0 to 2.5 µm
Envelope	Ø 125 x 180 mm cylinder
Mass	2 kg

Table 1: Field Selector Specifications

The stability requirement applies to closed loop regulation or slow tracking. It defines the dynamic range of the system which must then be at least 100'000.

3. FIELD SELECTOR MECHANISM DESCRIPTION

3.1. Suspension and Actuator Guiding

The pivotless tip-tilt mechanism implements frictionless supports of three linear actuators with a 3-rod suspension (Fig. 2) which allows the fine pointing mirror to combine the high static deflection range with a high frequency bandwidth and step response performance.

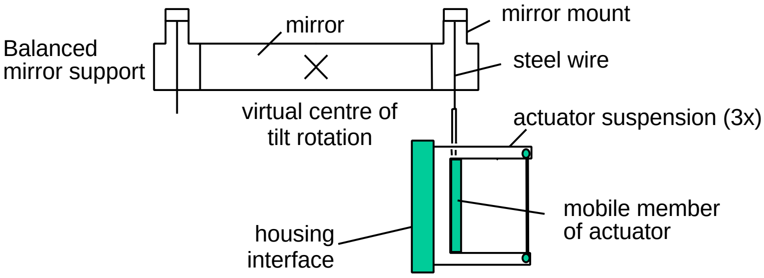

Fig. 2: Operating principle of 2-axes mirror suspension

Three ETEL electromagnetic linear motors (MLZ1) are set 120° apart with the mobile magnets mounted on frictionless flexure guides. The parallelogram flexure guides allow a linear movement of the mobile magnet of ±4 mm without backlash. Each actuator assembly is composed of four, individual hairpin linear guides manufactured using electro-discharge machining (EDM) from a monolithic Aluminium plate. The mirror is also supported by flexure elements. A central membrane in CuBe allows the tip-tilt movement around its centre of rotation while providing radial rigidity and stability. The central membrane is also manufactured using wire-EDM techniques cutting out slits to allow flexibility in the direction perpendicular to the membrane plane. The actuators are linked to the mirror through three steel wire rods attached through specially designed interface elements which provide the desired tip-tilt flexibility and guiding. The interface elements are epoxied directly to the mirror surface and bolted to the actuator on the other side.

3.2 Mirrors

The mirrors have been designed by CSEM and fabricated by Ceramique & Composites/Boostec (Bazet, France) in sintered silicon carbide (C&C SiC 100) for its stability, lightweight, very high stiffness and low inertia (Fig. 3). The thermal properties of SiC 100 present a combination of a low coefficient of thermal expansion with a very good thermal conductivity which is insensitive to thermal shocks[1]. The front side of the mirror has a non-porous SiC CVD coating to remove residual surface porosity prior to polishing. The polished mirrors (performed by Stigma Optique at Montgeron, France) are required to have an effective surface flatness of better than 30 nm rms over a diameter of 85 mm. The mirrors have been completed with a Silver coating (SILFLEX MKII) by Balzers in Liechtenstein. Numerous tests at each manufacturing stage of the mirrors have shown that they are well within the required specifications with measurements of better than 20 nm rms over 88 mm in surface flatness. The surface roughness has been measured at 0.2 nm rms and 2 nm peak-valley compared to a specification value of less than 2 nm rms. The backside of the mirror contains the actuator interface elements for the flexible rods, the targets for the inductive sensors and the central interface for the CuBe membrane. As far as we know, CSEM will be the first company worldwide to deliver SiC mirrors for an astrophysical experiment.

Fig. 3: Back side of SiC mirror for NAOS Field Selector

3.3 Position Sensors

Three Micro-Epsilon eddy current proximity sensors (DT110-T-U6-A-C3) provide the feedback information for the control loop. The sensors are contained within the mechanism structure and provide a noise level varying from 10 to 110 nm with the target distance (from 0 to 6.5 mm). The effect of the sensor noise to closed loop control is of course also affected by the sampling bandwidth.

Because of this varying sensor noise, the angular resolution of the mechanism will depend on the setting as shown below (Fig. 4) for two typical closed loop bandwidths.

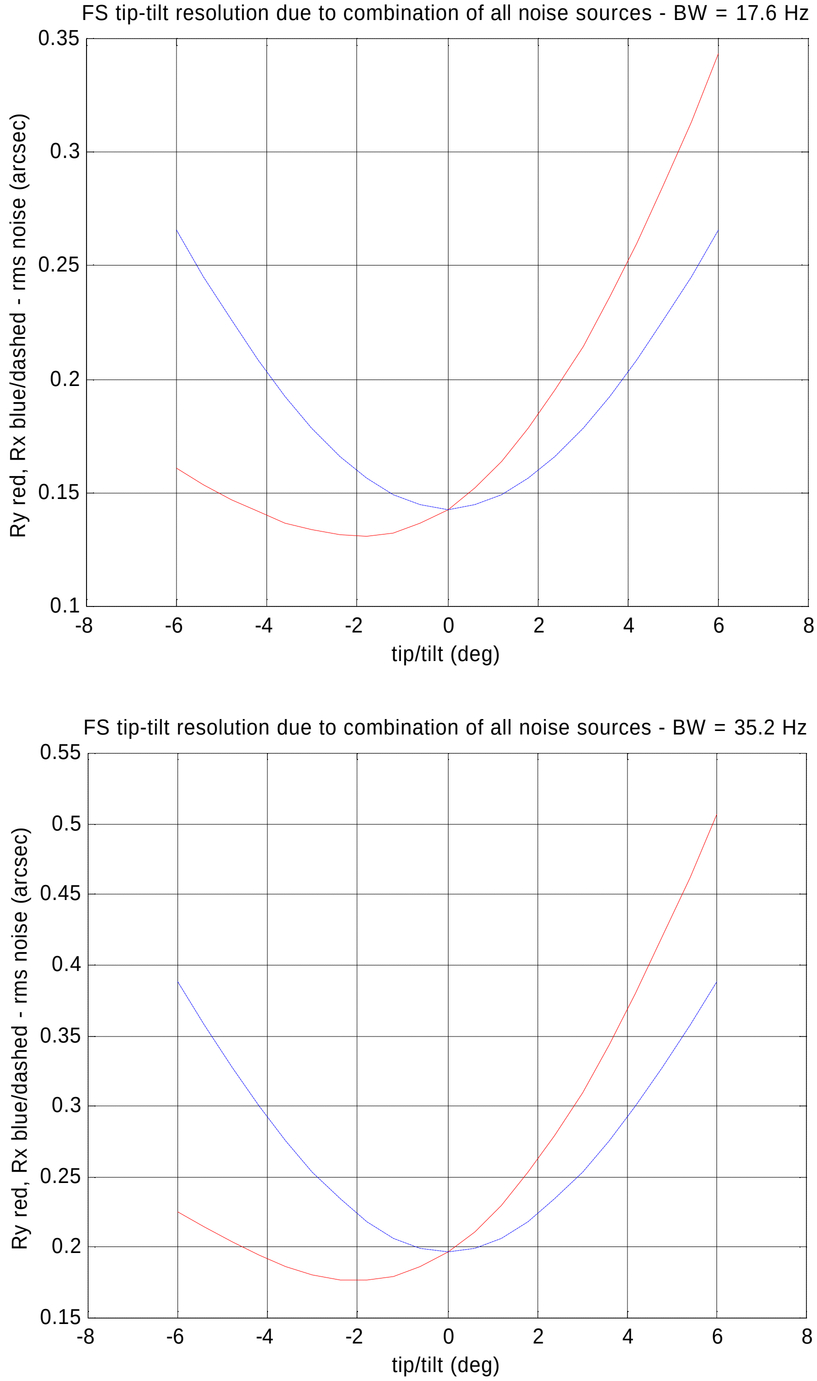

Fig. 4: Tip-tilt computed closed loop noise, for control bandwidths of respectively 17 and 35 Hz.

3.4 Mechanism Assembly

The field selector mechanism is shown below without the external cover where details of the motor assembly and suspension can be seen (Fig. 5). With the mirror removed (top view), the position of the sensors with respect to the actuators are apparent on the structure as well as the central membrane.

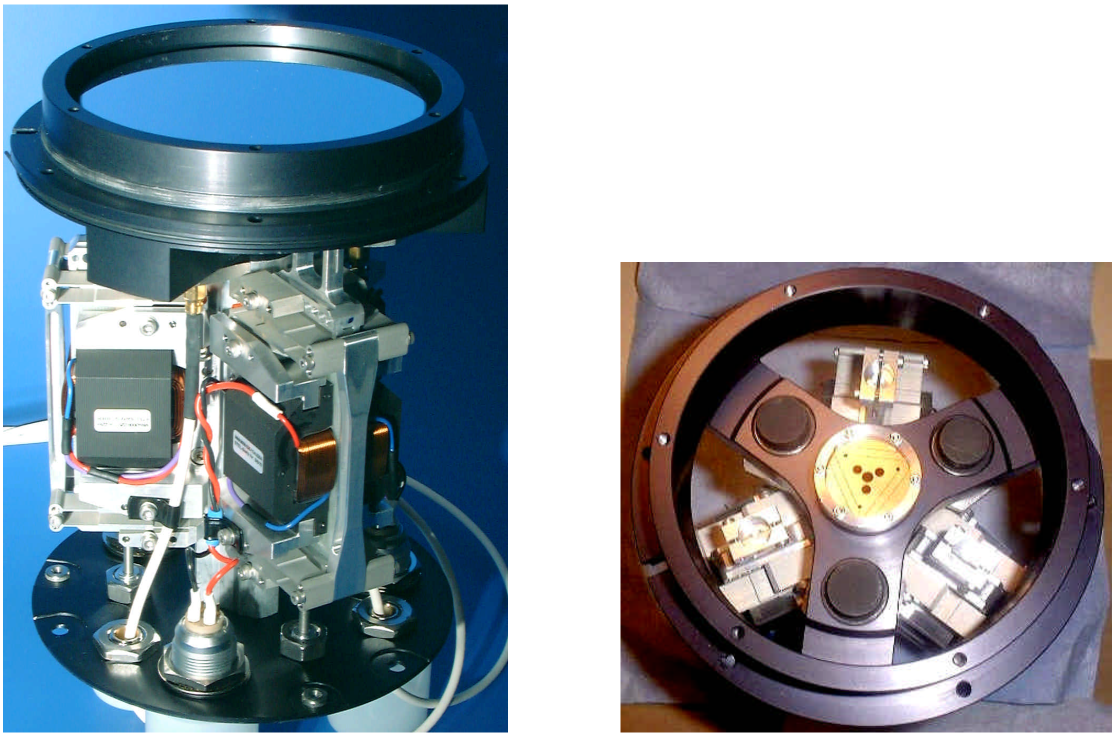

Fig. 5: Details of mechanism for NAOS Field Selector (with and without mirror)

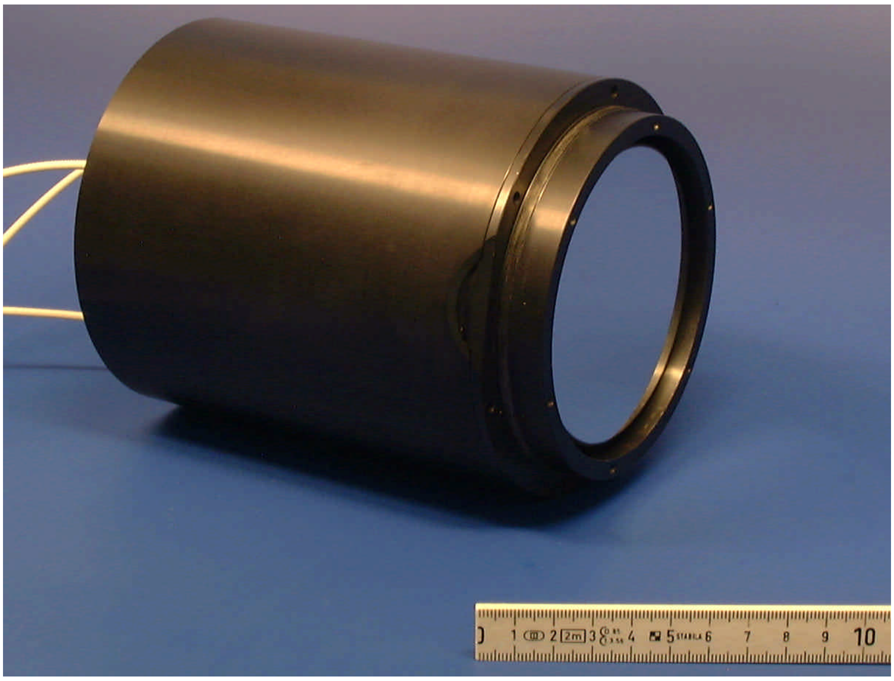

Fig. 6: Assembled tip-tilt-piston mechanism for NAOS Field Selector

4. CONTROL SYSTEM

The control system of the field selectors is targeted to the overall 17-bit accuracy objective and comprises both analog and digital elements: signal conditioners for the proximity sensors, motor amplifiers, a VME-bus control system with high resolution ADC and DAC boards.

To ensure the stability requirement in spite of possible drifts of the lower bits of the ADC, a CSEM custom electronic board performs, at regular intervals, a recalibration of the sensor signals with respect to a very stable voltage reference. During the time one loop is open for calibration, another channel is used to get information from the position sensor so that the system is virtually kept in closed loop at all times.

Analytical Model

The system to control the mechanism is presented in Figure 7. On the left is the actuator model and on the right the mechanism model. The upper part represents the mechanical model, the middle part the electrical model and the lower part the transfer function model.

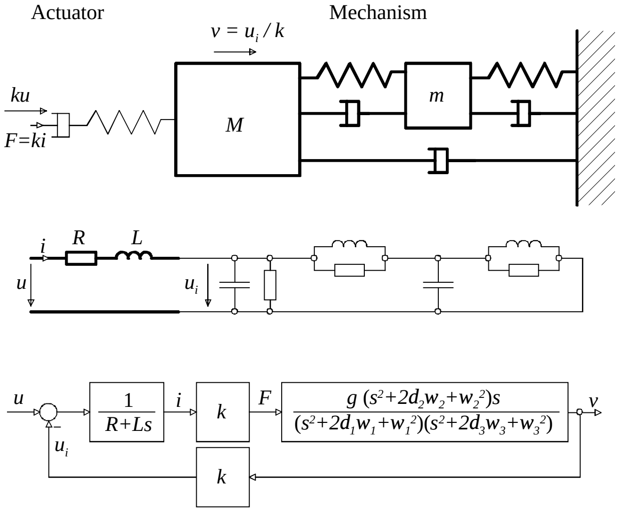

Fig. 7: Mechanism and Actuator Model

M is the mass of the actuator mobile part, whereas *m* is the mass of the rod linking the two hairpins. The springs and dashpots model the hairpins. The third dashpot takes into account other damping in the mechanical structure. *L* is the actuator inductance and *R* its resistance. As can be seen in Figure 8, the transfer function "position over current" has two resonances (the second one is caused by the rod linking the hairpin suspension).

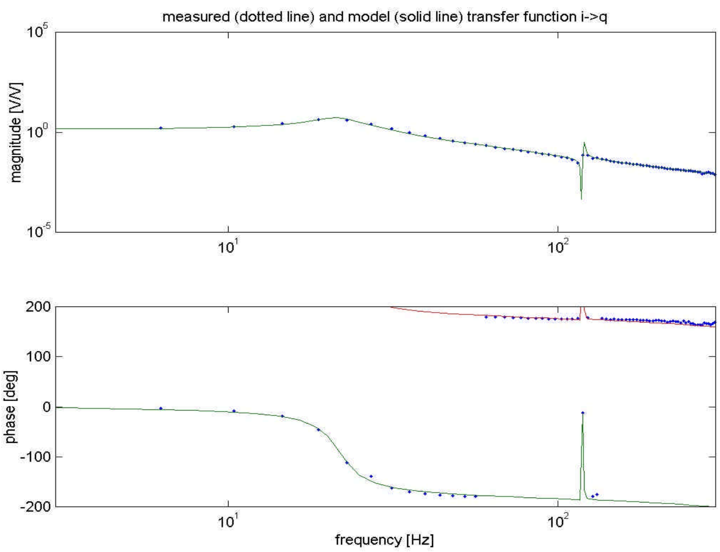

Fig. 8: Transfer function from current (~force) to position of experimental and simulation results

The current is controlled by the inner loop and the position by the outer loop as depicted in the closed loop system below (Fig. 9).

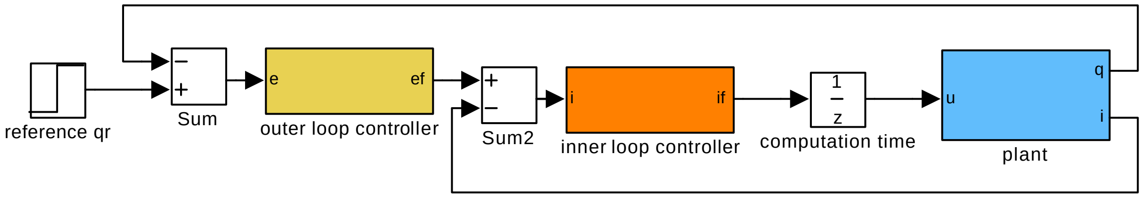

Fig. 9: Mechanism Controller

5. EXPERIMENTAL RESULTS

The results shown in this section were obtained using a "1D test bench" which consists of an identical actuator and position sensor assembly representing one axis of the mechanism and equipped with an interferometer for reference position measurements. The very low noise requirements for the angles is projected on the 1D test bench with the assumption that the different noise sources are independent. In practice, the 50 Hz residual noise or the temperature dependency leads to a strong correlation between axes, which moves the mirror in the piston direction for which the noise specification and temperature sensitivity is much less restrictive than for the angles. Thus, the independent noise source assumption is the worse case. Nevertheless, the achieved results for the 1D test bench are within the specifications.

The dynamic response to a small step (top of Fig. 10) of 15 mV is shown which is equivalent to 120 µm on the 1D test bench or 0.24° on the mechanism. The green curve with the overshoot is obtained by simulation, whereas the blue line is measured on the 1D test bench. They are not exactly identical everywhere since the real mechanism has an important hysteresis that has not been modeled in the simulation. The circles are the real position measured by the interferometer, and thus, without the position sensor noise. The bottom part of Figure 10 is a zoom of the position error with the two horizontal lines representing the maximum specified rms noise levels (±0.11 µm or 0.42 arcsec). Regarding the noise level, it seems to be higher than the specification only because the displayed curves include the sensor noise. If only the real position is considered, the noise is within the specification, as shown in Figure 11 based on a longer time interval. The settling time for the small step response of 0.24° is about 100 ms for the simulation and 160 ms for the experiment (a factor of 2 to 4 is to be gained to meet the 40 ms specification). Step function results between 0° and 12° amplitude are simulated in Figure 12 showing the variation in settling time with 0.6° being the amplitude from which the mechanism is within nominal specifications and surpassing the goal specifications at 9°.

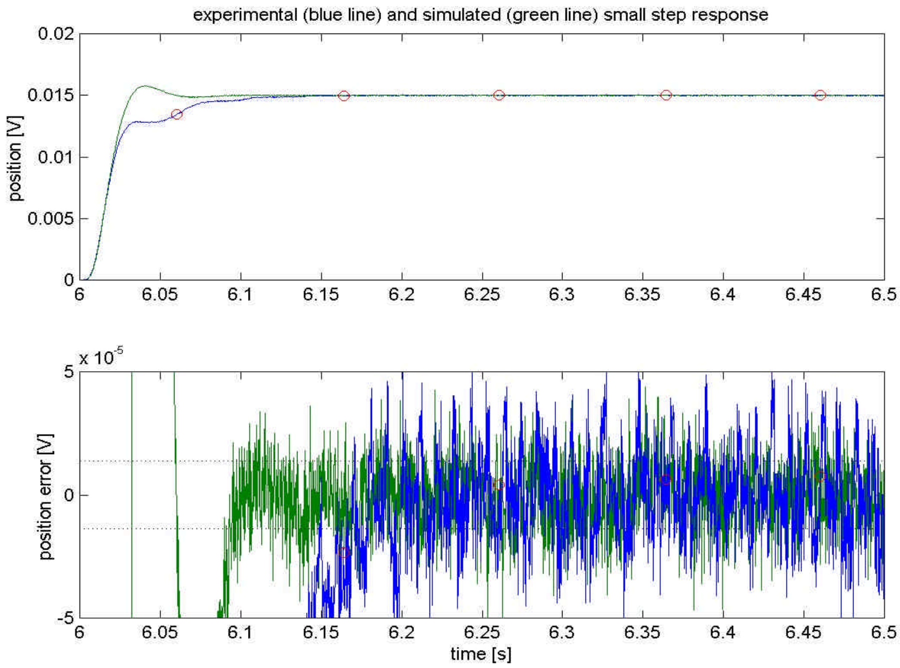

Fig. 10: Experimental and simulated small step response (1 V corresponds to 8 mm)

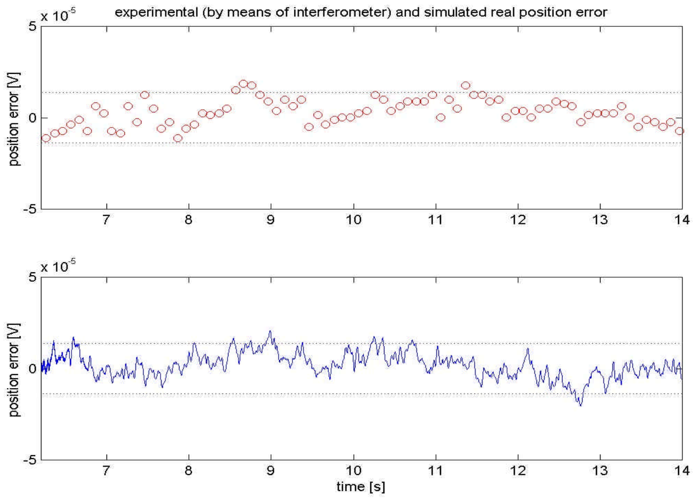

Fig. 11: Experimental (top) and simulated (bottom) mechanical stability (1 V corresponds to 8 mm)

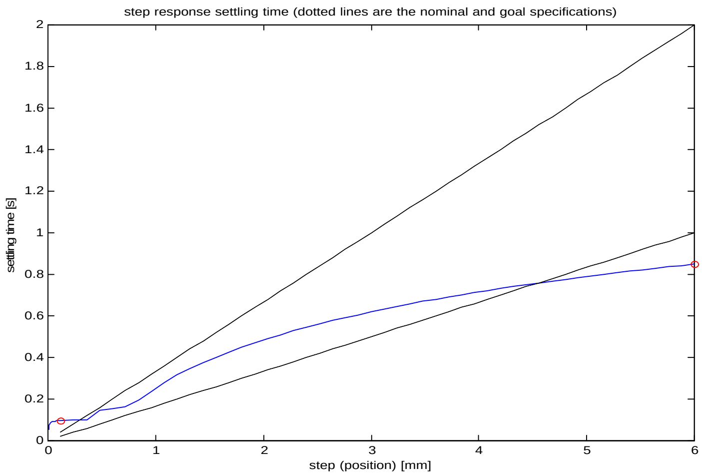

Fig. 12: Simulated settling response time as a function of step amplitude (6 mm = 12° tilt)

6. CONCLUSION

This work has demonstrated that a tip-tilt-piston mechanism for fine pointing applications based on electro-magnetic actuators and high resolution inductive sensors can meet stringent mechanical stability requirements such as the 0.42 arcsec rms over 20 minutes specified for NAOS. Stability and pointing performance has been met by incorporating a combination of techniques such as the use of flexures for frictionless guiding and suspension, a SiC mirror for low mass and high stiffness, a control system comprised of both analog and digital elements, signal conditioners and high resolution ADC and DAC interface boards. A special electronic board is also included which performs a recalibration of the sensor signals with respect to a very stable reference voltage. Simulation results were first verified experimentally on a 1D actuator test bench to evaluate performance characteristics and noise sources. Test results have confirmed that the achieved performance is within specifications and has allowed the simulation model to be validated prior to testing on the field selector mirror mechanisms.

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