Design and prototype performance of an innovative cryogenic tip-tilt mirror

Huub Janssen*[a], Maurice Teuwen[a], Ramón Navarro[b], Niels Tromp[b], Eddy Elswijk[b],
Hiddo Hanenburg[b]
[a]Janssen Precision Engineering, Azielaan 12, 6199AG Maastricht-Airport, The Netherlands
[b]NOVA - ASTRON, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands

ABSTRACT

Cryogenic mechanisms are needed for the alignment plan of MATISSE, a mid-infrared spectro-interferometer for the European Southern Observatory Very Large Telescope Interferometer (ESO VLTI) that combines up to four Unit Telescopes or Auxiliary Telescopes. Telescope beams are split into 16 beams that need to be aligned on the detector and corrected for OPD (Optical path difference) in order to create an interference pattern.

Alignment accuracy and stability specifications are of the order of nanometers and arcsec's. These specifications cannot be met by warm alignment nor by manufacturing tolerances, therefore 16 motorized tip-tilt units are needed that operate in a vacuum cryogenic environment.

Key aspects of the mechanisms are that the optical element and mechanism are combined in a compact single component, driven by self braking piezo actuators in order to hold position without power. The design, realization and test results of these mechanisms are presented.

Keywords: cryogenic, mechanism, tip-tilt, mirror.

1. INTRODUCTION

1.1 General

The European Southern Observatory (ESO) has planned a new instrument to be installed on the existing VLTI (Very Large Telescope Interferometer), on the mountain Cerro Paranal in Chile. This new instrument is called MATISSE, which stands for Multi-AperTure mid-Infrared SpectroScopic Experiment. It should combine images of up to four separate VLTI telescopes and thereby improve the capabilities of the interferometer and engage a new scientific prospective[1].

MATISSE is developed by a European consortium of several institutes and universities. The optical and infrared instrumentation division of NOVA (located at ASTRON facilities) is a lead player within this consortium. NOVA has involved Janssen Precision Engineering (JPE) to develop and test one of the key modules of the future instrument.

The VLTI is the flagship facility for European ground-based astronomy at the beginning of the third Millennium. It is the world's most advanced optical instrument, consisting of four Unit Telescopes with main mirrors of 8.2m diameter, and four movable 1.8m diameter Auxiliary Telescopes. The telescopes can work together to form a giant 'interferometer', allowing astronomers to see details up to 25 times finer than with the individual telescopes. The light beams are combined in the VLTI using a complex system of mirrors in underground tunnels where the light paths must be kept equal to distances less than 1 micrometer over a hundred metres. With this kind of precision the VLTI can reconstruct images with an angular resolution of milli-arcseconds, equivalent to distinguishing the two headlights of a car at the distance of the Moon.

---

* For detailed information contact huub.janssen@jpe.nl, phone +31 43 3585777, www.jpe.nl

Figure 1. ESO site on Cerro Paranal. The VLTI is formed by four Unit Telescopes with main mirrors of 8.2m diameter (large buildings) and four movable 1.8m diameter Auxiliary Telescopes (domed buildings). Picture by ESO.

1.2 MATISSE

MATISSE is designed to be a mid-infrared spectro-interferometer combining the beams of up to four different source telescopes of the VLTI. With this new instrument, the scientific area of long baseline optical interferometry will benefit from two major breakthroughs. First the wavelength range is extended with observed wavelengths from 3 to 15 micrometer, opening a new window to the universe. Secondly MATISSE will measure closure phase relations and thus offer an efficient capability for image reconstruction. It will for the very first time allow image reconstruction of small-scale regions in the mid-infrared wavelength domain and thus allow an investigation of these structures.

In order to achieve its performance the optical beams in MATISSE are split various times[2]. First for every telescope the low wavelengths are separated from the high wavelengths. Later every single beam is split again in order to create photometric beams and an interferometric pattern together with the other three telescopes. Finally a spectrum interference pattern is created on the detector. Image reconstruction is done from these interference patterns. Alignment is crucial, because the interfering beams have to overlap exactly on sub-detector pixel accuracy. Since infrared radiation is created by heat, the MATISSE instrument must be cooled to cryogenic temperatures down to 8 Kelvin. These temperatures are only achieved in a high vacuum environment.

It has been investigated that the required angular accuracies of all the mirrors which are used for alignment of all individual beams cannot be guaranteed at cold working temperature based on fixed mountings and accurate tolerance budgeting. A motorized tip-tilt mirror alignment mechanism which can operate in this cryogenic environment is therefore required as an enabling technology for the development of the MATISSE instrument[3]. Based on this importance for the instrument as a whole, it is decided by NOVA to demonstrate the feasibility of the TTM at an early stage by means of a prototype.

This demonstration project has been performed by Janssen Precision Engineering in cooperation with NOVA-ASTRON within a limited timeframe of only 4 months, a TTM concept has been developed, built and successfully tested.

2. SPECIFICATIONS

The TTM basically consists of a nearly rectangular mirror with a typical dimension of 33 mm, and a baseline thickness of about 8 mm. Tip and tilt of the mirror should be manipulated with microrad's resolution within a range of + and - several millirad's. Operation should be possible in both ambient as cryogenic (30K – 100K) environment, though final use will be in the cryogenic environment at 40 K.

Table 1. Specification overview tip-tilt mechanism for MATISSE

Description	**Specification**
Mirror dimension (square)	33 mm (XY)
Tilt Range	> ±5.24 mrad
Tilt Resolution	1.22 microrad
Tip – Tilt crosstalk	< 10 %
Short term stability	0.70 microrad/hr
Long term stability (typically 10 yrs)	1.30 microrad
Mirror flatness	63 nm (pk-pk)
Parasitic mirror displacement – in plane – perpendicular	 < 0.2 mm < 100 micrometer
Operational temperature	40 K
Design envelope	75mm (X) x 75mm (Z) x 35mm (Y)

3. CONCEPT DESIGN

Within the NOVA-ASTRON optical and infrared instrumentation division, an extensive inventory has been performed on commercially available actuators that can be used in cryogenic applications. In general it can be said that piezo actuators are suitable for this environment, though it should be noted that movement efficiency is affected by the low temperature.

For this particular mechanism, it is decided to use the PiezoLEG™ actuator from the Swedish company PiezoMotor Uppsala AB as a baseline. The actuator has only a small envelope (22mm x 11mm x 20mm). The output motion is via a ceramic bar, which is claimed to have a movement resolution in the nanometer range. To compensate (as far as possible) for the actuator’s efficiency loss in cryogenic temperatures, a custom electronic amplifier stage has been build by NOVA which creates a higher output voltage to the PiezoMotor.

With the above mentioned input JPE started the evaluation of possible mechanism concepts. Chosen was a direct drive mechanism with a lever in order to enhance resolution. A simplified 1-dimensional representation of this concept can be seen in figure 2. By implementing a second actuator in a orthogonal location w.r.t. the fixed pivot, the mechanism can be extended to a full 2-dimensional Tip-Tilt mechanism.

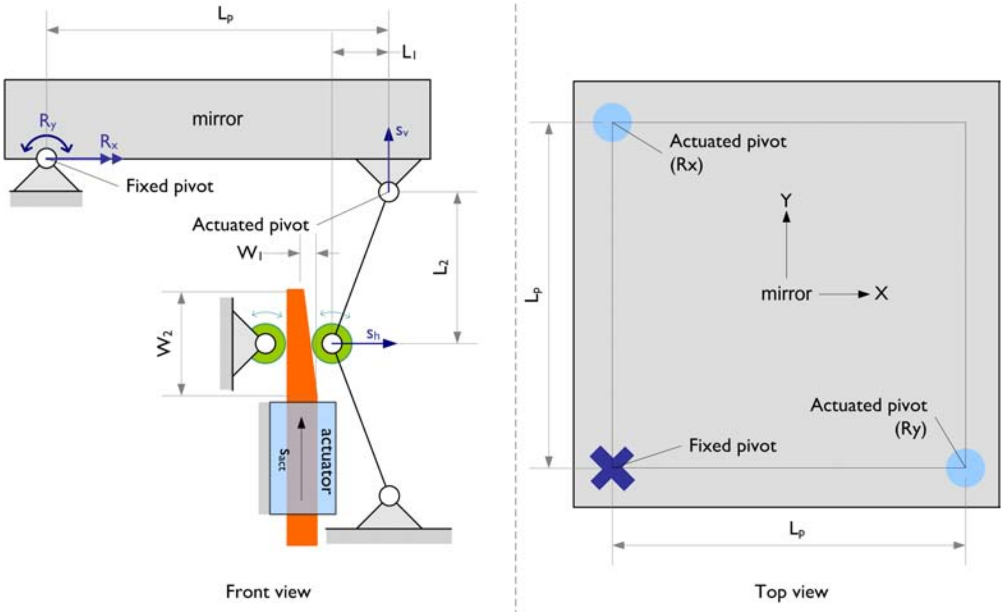

Figure 2. Tip-tilt mechanism concept design

The mirror body is supported on three pivots. The base pivot directly connects the mirror body to the base. The two other pivots are connected to the base by a toggle mechanism. The toggle mechanism is operated by the piezo actuator via a wedge on the ceramic bar of the actuator.

The positive distinctive characteristics of the concept are:

1. This concept accommodates 2 serial reductions. Firstly there is a wedged shape on the actuator output bar, which transfers the actuator motion only fractionally into the mechanism. Secondly there is the toggle mechanism which transfers the horizontal input motion only fractionally to a vertical output motion. Thereby the concept enables to implement a large reduction between actuator input movement and mirror output movement. This enables less demanding use of actuator w.r.t. actuation force, displacement resolution and position stability.
2. Tip and Tilt actuation is separate though integral part of the design; no stacked layout where the Tip-mechanism is mounted on top of a Tilt-mechanism. This benefits the stiffness of the mechanism, and it enables a monolithic manufacturing approach which is beneficial for stability behavior.
3. Tip and Tilt actuation are fully orthogonal; each actuator is directly linked to a single output rotation without disturbing the other output rotation.

4. REALISATION OF TIP TILT MECHANISM

The realized design is depicted in figure 3. The mechanism is realized as a monolithic body machined (milling) from Aluminium T6061-T6. Milling and polishing have been performed in the mechanical workshop of NOVA-ASTRON.

The two toggle mechanisms are point symmetrically implemented in the mechanism. The mirror is an integral part of the mechanism and is polished as a final step in the manufacturing process[4].

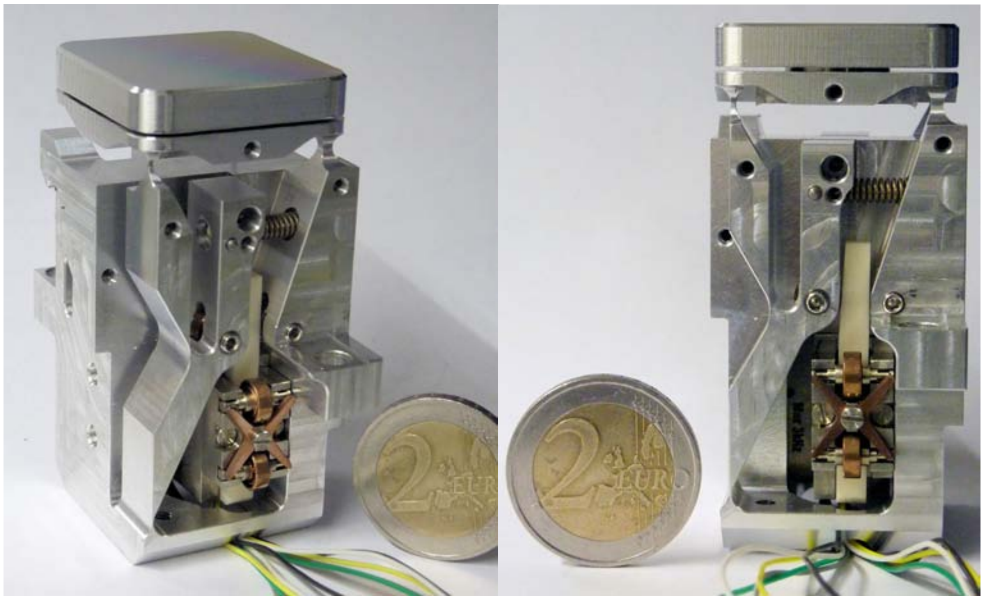

Figure 3. Tip-tilt mechanism realization

The pivots are realized as elastic hinges. The two lower hinges of the toggle mechanism have a single pivot axis (line pivot), the upper hinge (to the mirror) has two orthogonal pivot axis' (point pivot) to accommodate rotations introduced by the other actuator. An integral end of stroke protection is implemented per toggle mechanism, in order to prevent damage to the hinges.

A bearing is situated at the level of the 'knee' of the toggle mechanism. This bearing is pushed against the wedge shape of the ceramic actuator bar by a tension spring. As the actuator bar is not constrained in this direction by the actuator guiding itself, a support bearing is implemented directly opposite to the toggle mechanism bearing. In this way the actuator bar is able to self-align within the mechanism. The bearings are currently of the same type as the actuator bearings, though the use of commercially available hybrid bearings is also possible.

For the dimensioning of the elastic pivots, the cryogenic material properties have been accounted for. The data on E-modulus and yield/shear strength for Aluminum T6061-T6 are represented in figure 5. Although it might seem quite logical that the E-modulus is higher at lower temperatures, it might be contra-intuitively to see that the yield and tensile stress levels also are higher at lower temperatures.

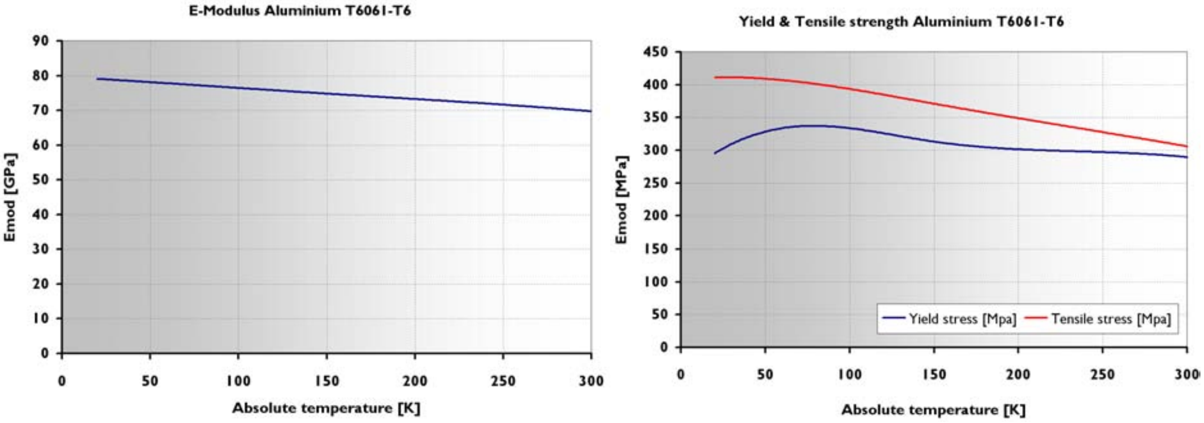

Figure 4. Aluminum properties at cryogenic temperatures

3.1 Mirror flatness

Mirror flatness is an important specification for the TTM. Therefore FEA calculations have been performed to optimize the performance of the design on this feature. As design parameters to optimize the flatness performance it has been chosen to use

1. The dimension of the base pivot. By reducing the thickness of the base pivot, the pivot becomes weaker. Less force is involved when moving the mirror to a certain Tip/Tilt orientation. As these forces are propagated as a bending moment through the mirror body, this will decrease the deformation of the mirror.
2. Diameter of a saw cut groove in the mirror body, parallel to the mirror surface. The idea behind is that the bending moments through the body are contained within the lower part, which becomes isolated from the mirror surface which is in the upper part of the body.

Both parameters seem to have a more or less linear effect on the flatness; reduction of the input parameter by a factor 2 improves flatness behavior with also by roughly a factor 2. It has been decided to use the effect of both parameters to limit the mirror deformation. The expected deformation of the mirror at full Tip/Tilt stroke is then expected to be pk-pk value is 27 nm, which is well below the design target.

3.2 Resonance frequencies

As a design verification, the resonance frequency of the TTM mechanism has been calculated. There has been set no specific requirement for this parameter, though common engineering sense dictates that a resonance frequency of >> 100 Hz is preferred so the mechanism will not be affected by system dynamics.

By FEA it is determined that the first resonance mode is a Rz mode of the mirror body at approximately 355 Hz, where the two toggle mechanisms allow a tangential movement of the mirror around the base pivot. The second mode is a combined Tip/Tilt movement at approximately 1590 Hz, as a result of a local Z movement of the mirror body at the output of the two toggle mechanisms and with the base pivot as a center of rotation.

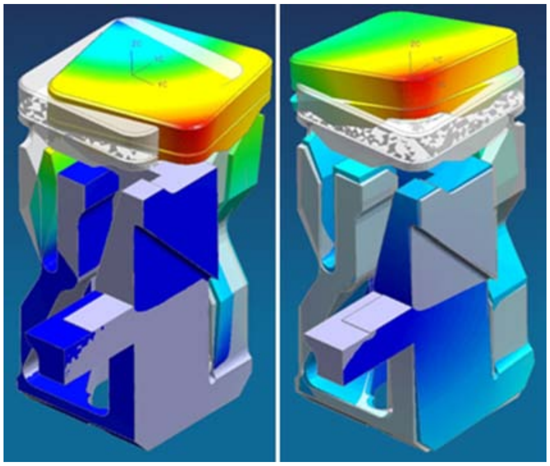

Figure 5. First resonance modes of the mechanism

5. TEST RESULTS

The realized mechanism has been tested first in ambient conditions as a design validation. The measurements indicated that the behavior of the mechanism was in quite perfect resemblance with the theoretical models which have been made to predict the performance of the system.

After that the mechanism has been installed in a cryostat at ASTRON facilities. The cryostat has been evacuated and cooled down to 20K by a closed cycle cooler. Flatness of the mirror surface has been measured by an interferometer through a window of the cryostat. Also the Tip/Tilt movement has been done from outside the cryostat by using a autocollimator with an angular resolution of 0.1 arc second (0.49 micro-radians).

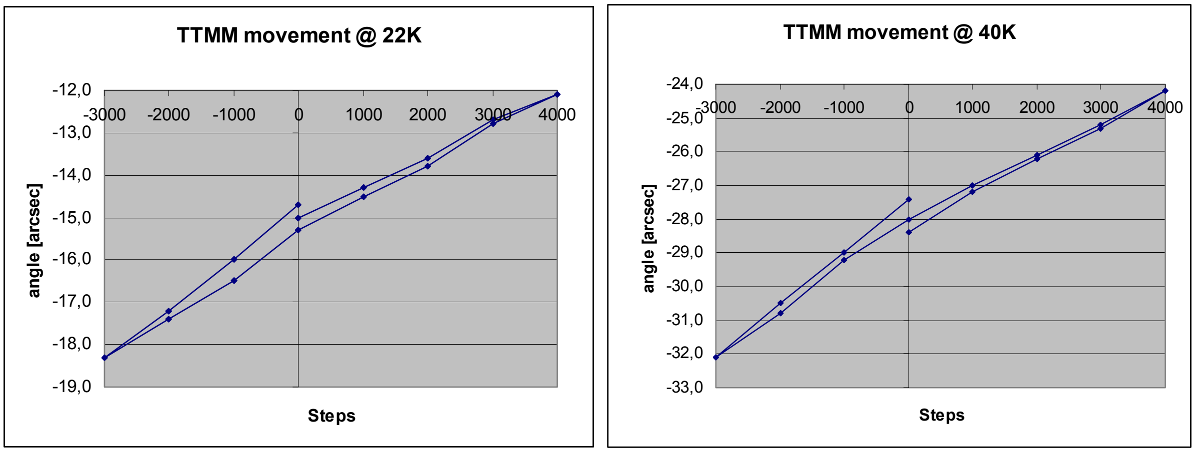

Figure 6. Cryogenic testing of the Tip-Tilt mirror mechanism.

The measured angular resolution of the TTMM is 1 miliarcsec per step. These steps are made in the 128p wfm (points waveform) mode. Higher resolution may be obtained by the 2048p wfm mode. The linearity and direction dependence of the response is better than expected (there are no requirements on these parameters).

Unfortunately the motors seize functioning after warming up. It seems that the Piezo stack is damaged by either an electro static discharge or some kind of delamination. A detailed failure root cause analysis has been started with systematic tests to investigate this issue as well as possible solutions to prevent future motor damage.

An overview of the key performance results at cryogenic temperature can be seen below.

- Operational temperature during test	20 … 40 K
- Tip/Tilt resolution	< 0.2 arcsec (= 1.0 microrad)
- Tip/Tilt crosstalk	< 7 %
- Mirror flatness (in extreme Tip/Tilt orientation)	< 0.15 wavelength P-V @ 633nm (= 90 nm P-V)

6. CONCLUSIONS

The Cryogenic tip tilt mirror development has been proven to be a success and points out that integration of commercially available parts into a mechanism is more than combining components.

In the concept phase essential trade off's on opto-mechatronic system design have to be made in order to achieve the requirements. Examples are: the kinematic stress-free mirror support, complete play-free and frictionless actuation and the essential calculations and simulations.

Last but not least of all is the good cooperation between Janssen Precision Engineering and NOVA-ASTRON part of the success of this project.

REFERENCES

[1] Lopez, B., "MATISSE: perspective of imaging in the mid-infrared at the VLTI",Proc. SPIE 7734,34, 2010
[2] Tromp, N., "MATISSE cold optics opto-mechanical design", Proc. SPIE 7734, 63, 2010
[3] Elswijk, E., "The innovative MAIT plan for the MATISSE cold optics, comprising an unprecedented 300 cryogenic optical components", Proc. SPIE 7739, 167, 2010
[4] Ter Horst, R., "Directly polished lightweight aluminum mirror", Proc. SPIE 7018, 08, 2008

ACKNOWLEDGEMENTS

MATISSE is an instrument defined and built by a consortium of French (OCA), German (MPI for Astronomy, MPI for Radioastronomy, University of Kiel), and Dutch (NOVA-ASTRON, Leiden Observatory and NWO) institutes.