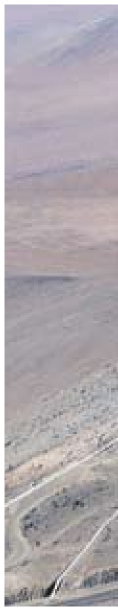
Cryogenic tip-tilt an astronomical



The development of astronomical instruments has always been a field where precision engineering and optical design meet. Latest developments also involve the implementation of precision engineering and mechatronic control in cryogenic environments. With almost twenty years of experience in precision engineering, in both ambient and vacuum environments, Janssen Precision Engineering has over the years expanded its working field to the cryogenic environment. A recent activity is the development of a cryogenic tip-tilt mechanism for a future astronomical instrument.

• *Maurice Teuwen, Har Craenen and Huub Janssen* •

The European Southern Observatory (ESO) has planned a new instrument to be installed on the existing VLTI (Very Large Telescope Interferometer), which is located on the mountain Cerro Paranal in Chile. This new instrument is called MATISSE, which stands for Multi-AperTure mid-Infrared SpectroScopic Experiment. It will combine images of up to four separate VLTI telescopes and thereby improve the capabilities of the interferometer and open a new scientific prospective.
MATISSE is being developed by a European consortium of several institutes and universities. The optical and infrared instrumentation division of the Netherlands Research School for Astronomy NOVA (located at the facilities of ASTRON, the Netherlands Institute for Radio Astronomy) is a lead player within this consortium. NOVA has engaged Janssen Precision Engineering (JPE) to develop and test one of the key modules of the future instrument.

Giant interferometer

The VLTI is the flagship facility for European ground-based astronomy at the beginning of the third millennium; see Figure 1. It is the world's most advanced optical instrument, consisting of four unit telescopes with main mirrors of 8.2 m diameter, and four movable 1.8 m 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 within 1 μm 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 on the moon.

mechanism for instrument

Figure 1. ESO site on Cerro Paranal. The VLTI is formed by four unit telescopes with main mirrors of 8.2 m diameter (large buildings) and four movable 1.8 m diameter auxiliary telescopes (small domed buildings). (Picture: ESO)

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. Firstly, the wavelength range is extended with observed wavelengths from 3 to 15 μm, 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. Firstly, for every telescope the low wavelengths are separated from the high wavelengths. Later, every single beam is split into three in order to create beam pairs with the beams of the other three telescopes. Finally the beams are duplicated in a special way creating a spectrum with both a positive and a negative interference pattern. Image reconstruction is done from these interference patterns, 24 in total. Alignment is crucial, because the interfering beams have to overlap exactly on the detector pixels. Since infrared radiation is created by heat, the MATISSE instrument must be cooled to cryogenic temperatures down to 8 Kelvin. These temperatures can only be achieved in a high-vacuum environment.
From investigations it has been concluded that the required angular accuracies of all the mirrors that are used for alignment of all individual beams cannot be guaranteed at low working temperatures using fixed mountings with accurate tolerance budgeting. A motorized tip-tilt mirror alignment mechanism that can operate in this cryogenic environment is therefore required as an enabling technology for the development of the MATISSE instrument. Based on this importance for the instrument as a whole, it was decided by NOVA to demonstrate the feasibility of the tip-tilt mechanism (TTM) at an early stage by means of a prototype. This demonstration project has been performed by Janssen Precision Engineering. Within a limited timeframe of only four months, a TTM concept was developed, built and successfully tested.

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 resolution within a range of + and - several millirad's. Operation should be possible in both the ambient and the cryogenic (30-100 K) environment, though final use will be in the cryogenic environment at 40 K.

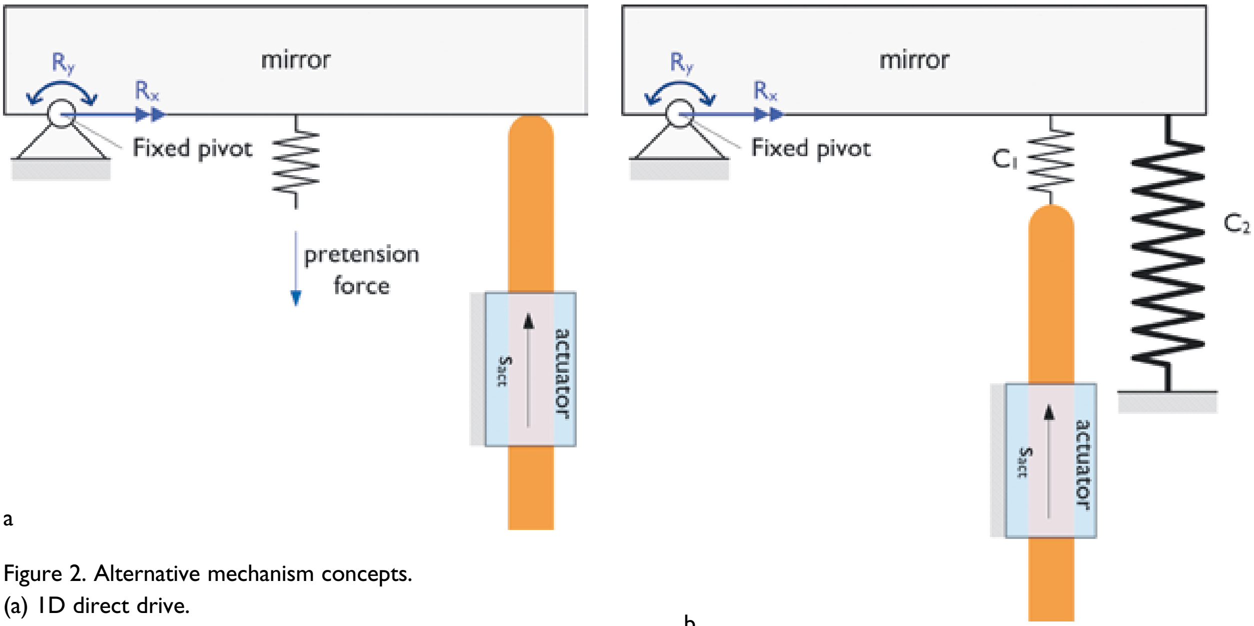


Figure 2. Alternative mechanism concepts.
(a) 1D direct drive.
(b) 1D elastic reduction.

Specifications include:

• Mirror dimension (square)	≈ 33 mm (X-Y)
• Tilt range	> ±5.24 mrad
• Tilt resolution	< 1.22 µrad
• Tip-tilt crosstalk	< 10%
• Short-term stability	< 0.70 µrad/hr
• Long-term stability (typically 10 yrs)	< 1.30 µrad
• Mirror flatness	< 63 nm (pk-pk)
• Parasitic mirror displacement – in plane	< 0.2 mm
• Parasitic mirror displacement – perpendicular	< 100 µm
• Operational temperature	40 K
• Design envelope	75 mm (X) x 75 mm (Z) x 35 mm (Y)

Actuator baseline

Within NOVA's optical and infrared instrumentation division, an extensive inventory was 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 was decided to use the PiezoLEG™ actuator from the Swedish company PiezoMotor Uppsala AB as a baseline. The actuator has only a small envelope (22 mm x 11 mm x 20 mm). 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 amplifier stage was built by NOVA that supplies a higher output voltage to the PiezoMotor.

TTM concepts

With the above mentioned input, JPE started the evaluation of possible mechanism concepts. The first major issue in the conception of a feasible concept was whether or not to use a 'direct drive' principle. In the direct drive, the actuator is directly connected to the mirror without any further reduction. A simplified 1-dimensional representation of this concept is shown in Figure 2a. By implementing a second actuator in an orthogonal location with respect to the fixed pivot, the mechanism can be extended to a full 2-dimensional tip-tilt mechanism.

Although the concept is very attractive due to its simple nature, with some basic analyses it was soon proven that this concept is not a match for the given specifications. The required angular resolution requires a stepping resolution which cannot be met by the actuator even in ambient conditions. Moreover, the limited actuation force has to cope directly with the angular stiffness of the fixed mirror pivot which cannot be made sufficiently weak within practical dimensioning. Taking into account the performance loss – both in resolution and force – of the actuator in cryogenic conditions, this concept was soon eliminated.

The alternative to a direct-drive mechanism is to implement a reduction between the actuator's input movement and the mirror's output movement. This can be realised by an elastic reduction mechanism, as conceptually visualised in Figure 2b. By tuning the stiffness ratio between C_1 and C_2, a reduction between actuator movement and mirror output movement can be realised. Although there is a discrepancy between optimisation for a low drive force on one hand and a high natural angular frequency on the other hand, this can yield a feasible design as far as resolution and force are concerned. The reason why this

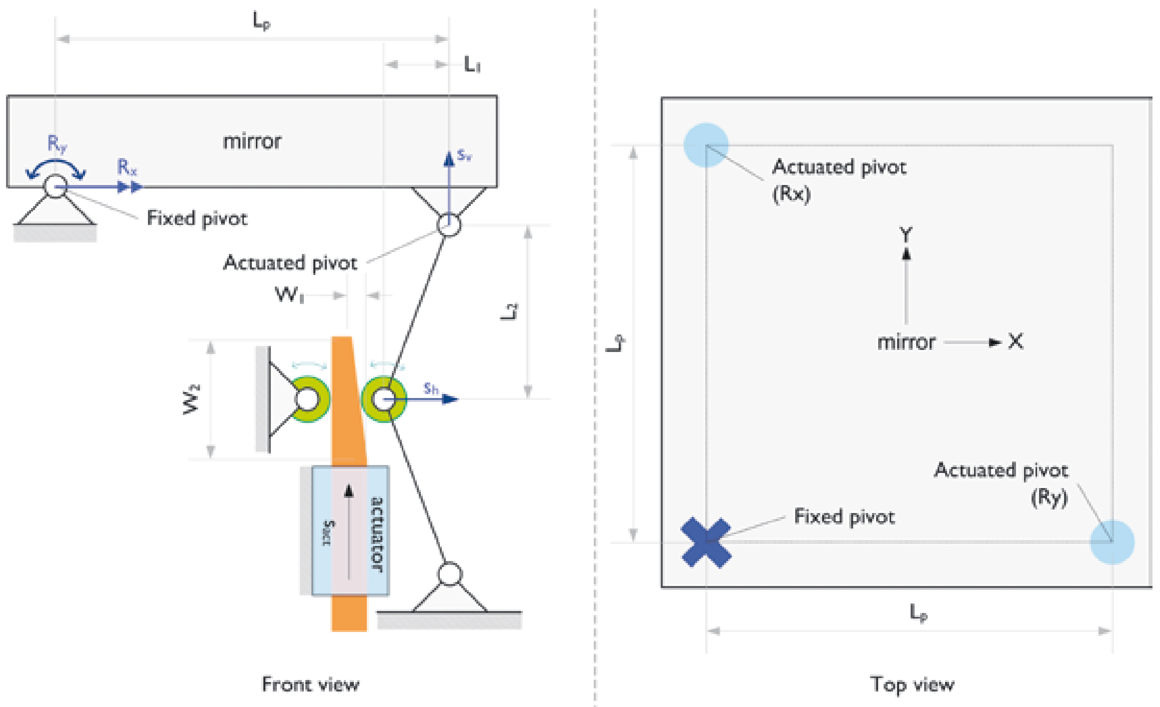


Figure 3. Tip-tilt mechanism concept.

concept was finally discarded is the uncertain stability behaviour of the springs and thereby the mechanism.
In this case, a better option for realising the reduction is to use a linkage mechanism which is based on a geometrical reduction of the movement. After weighing several alternatives, the toggle mechanism in Figure 3 was chosen the concept to be used for the TTM.
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. It is operated by the piezo actuator via a wedge on the ceramic bar of the actuator.

The positive distinctive characteristics of the concept are:

- This concept accommodates two 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 the actuator with respect to actuation force, displacement resolution and position stability.
- Tip and tilt actuation are separate though integral parts of the design; there is 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.
- Tip and tilt actuation are fully orthogonal; each actuator is directly linked to a single output rotation without disturbing the other output rotation.

Input-output relation

In order to obtain the relation between the actuator input and the mirror output movement, the following three movement transformations are combined:

1. Actuator bar movement S_{act} to toggle mechanism 'knee' displacement S_h:

$$S_h = \frac{W_1}{W_2} \cdot S_{act}$$

2. Toggle mechanism 'knee' displacement S_h to mirror support Z displacement S_v:

$$S_v = 2\frac{L_1}{L_2} \cdot S_h$$

3. Mirror support S_v to mirror angular displacement tip/tilt:

$$R_{xy} = \frac{S_v}{L_p}$$

Combining the equations yields the following input-output relation:

$$R_{xy} = \frac{2}{L_p} \cdot \frac{L_1}{L_2} \cdot \frac{W_1}{W_2} \cdot S_h$$

With realistic dimensions the transformation between linear input actuator motion and angular mirror output movement is then 0.81 μrad/μm. The pure linear movement reduction ratio between the linear output motion on the mirror (S_v) and the linear input actuator motion (S_{act}) is then 0.022 μm/μm (ratio 1 : 46). In other words, the specified

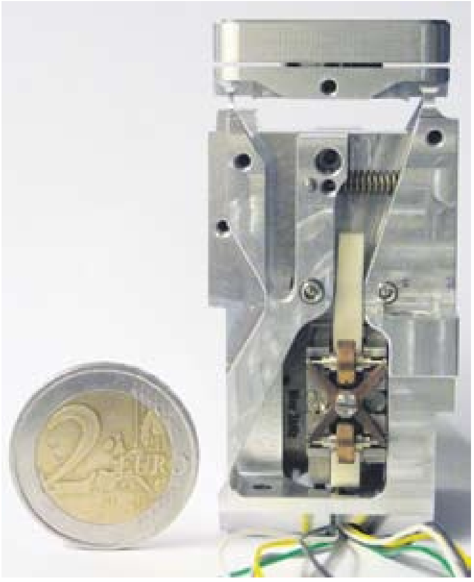



Figure 4. Two views of the realised tip-tilt mechanism.

angular tip/tilt resolution of 1.22 μrad equals a displacement resolution of the actuator bar of 1.51 μm. And the specified angular tip/tilt range of +/- 5.24 mrad equals a displacement resolution of the actuator bar of +/- 6.47 mm. These are feasible requirements for the actuator.

Actual design

The actual design is depicted in Figure 4. The mechanism was realised as a monolithic body machined (milling) from Aluminum T6061-T6. Milling and polishing have been performed in the mechanical workshop of 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.

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 axes (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 were accounted for. The American National Institute of Standards and Technology (NIST) presents an extensive database on its website (cryogenics.nist.gov) with cryogenic properties for typical construction materials.
The data on E-modulus and yield/shear strength for Aluminum T6061-T6 that are listed on this site are represented in Figure 5. Although it might seem quite logical that the E-modulus is higher at lower temperatures, it might be counter-intuitive to see that the yield and tensile stress levels also are higher at lower temperatures!

Mirror flatness

Mirror flatness is an important specification for the TTM. Therefore finite-element analysis (FEA) calculations were performed to optimize the performance of the design with respect to this feature. As design parameters to optimise the flatness performance it was decided to use:

- 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 this force is propagated as a bending moment through the mirror body, this will decrease the deformation of the mirror.
- the diameter of a saw cut groove in the mirror body, parallel to the mirror surface.
  The underlying idea is that the bending moments through the body are contained within the lower part, which becomes isolated from the mirror surface, 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 behaviour also by roughly a factor 2. It was 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 27 nm (peak-peak value), which is well below the design target.

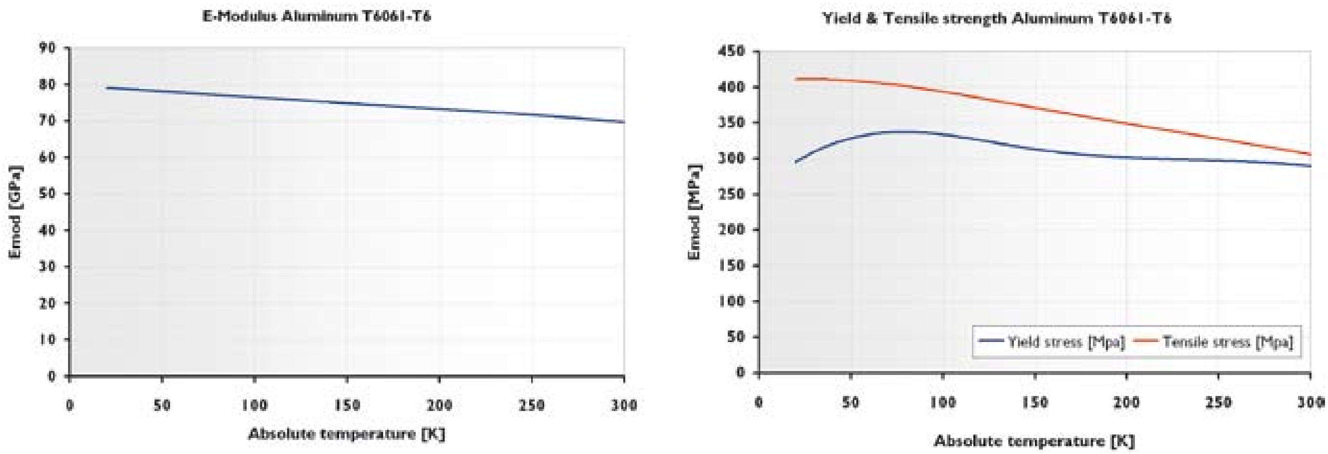


Figure 5. Aluminum T6061-T6 properties (E-modulus and yield/shear strength) against temperature.

Resonance frequencies

As a design verification, the resonance frequency of the TTM was calculated. No specific requirement had been set for this parameter, though common engineering sense dictates that a resonance frequency of >> 100 Hz is preferred, so that the mechanism will not be affected by system dynamics.
By FEA it was 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; see Figure 6. The second mode is a combined tip/tilt movement at approximately1,590 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.

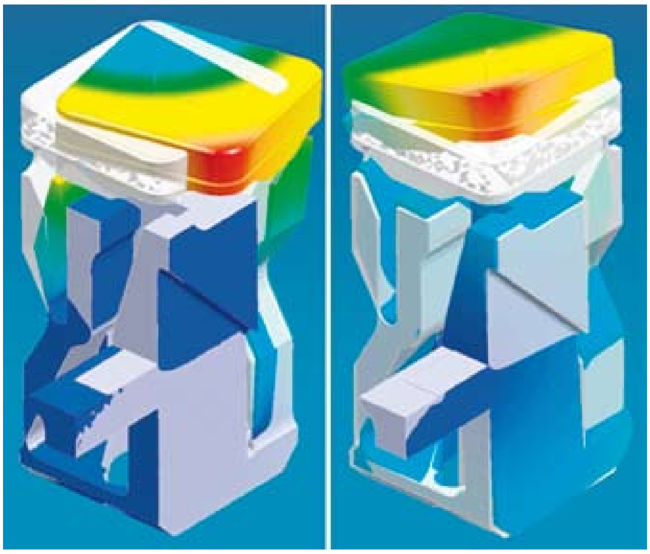


Figure 6. On the left the first resonant mode (355 Hz), on the right the second one (1,590 Hz).

Test results

The realised mechanism was tested first in ambient conditions as a design validation. The measurements indicated that the behaviour of the mechanism was in quite perfect resemblance with the theoretical models which were made to predict the performance of the system.
After that, the mechanism was installed in a cryostat at ASTRON facilities. The cryostat was evacuated and cooled down to 20 K by a closed-cycle cooler. Flatness of the mirror surface was measured by an interferometer through a window of the cryostat. Also the tip/tilt measurement was achieved from outside the cryostat by using an autocollimator with an angular resolution of 0.1 arcsecond (0.49 μrad).
Key performance results at cryogenic temperature:

- Operational temperature during test: 30-40 K
- Tip/tilt resolution < 0.2 arcsec (= 1.0 μrad)
- Tip/tilt crosstalk < 7 %
- Mirror flatness (in extreme tip/tilt orientation) < 0.15 λ P-V @ 633nm (= 90 nm peak-valley (P-V))

Authors' note

The authors work at Janssen Precision Engingeering (JPE) in Maastricht, the Netherlands, Maurice Teuwen as a system engineer, Har Craenen as a senior mechanical engineer, and Huub Janssen is the managing director.
The project described in this article was executed by JPE in cooperation with the optical and infrared instrumentation division of NOVA located at ASTRON facilities. The authors would like to thank the NOVA/ASTRON organisation, and in particular Ramon Navarro, Niels Tromp and Eddy Elswijk for their professional expertise in the realisation of this joint project, and NOVA director Wilfried Boland for initiating the project.

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