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# Flexure-based alignment mechanisms: Design, development and application

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## ABSTRACT

For high accuracy alignment of optical components in optical instruments TNO TPD has developed dedicated, monolithic, flexure-based alignment mechanisms, which provide accuracies below  $0.1 \mu\text{m}$  and  $0.1 \mu\text{rad}$  as well as stabilities down to picometers per minute.

High resolution, high stability alignment mechanisms consist of an adjustment mechanism and a locking device. Complex monolithic flexure-based mechanisms are designed to align specific degrees of freedom. They are realized by means of spark erosion. The benefits of these mechanisms are no play, no hysteresis, high stiffness, a simplified thermal design and easy assemblation. The overall system can remain a passive system, which yields simplicity. An actuator is used for positioning. Locking after alignment is mandatory to guarantee sub-nanometer stability per minute. A proper design of the locking device is important to minimize drift during locking.

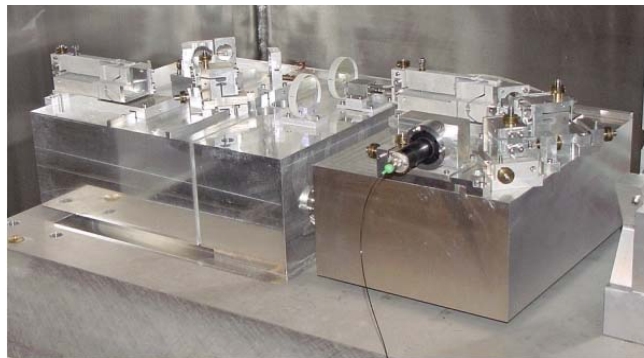
The dedicated alignment mechanisms presented here are based on: (a) the results of an internal ongoing research program on alignment and locking and (b) experience with mechanisms developed at TNO TPD for high precision optical instruments, which are used in e.g. a white light interferometer breadboard (Nulling) and an interferometer with picometer resolution for ESA's future cornerstone missions "DARWIN" and "GAIA".

**Keywords:** Opto-mechanics, alignment, flexures, locking

## 1. INTRODUCTION

TNO TPD develops optical systems and instruments used for lithography and space, in particular Earth observation and science instruments. TNO TPD is involved in the development process from feasibility studies and design to the manufacturing and qualification of flight hardware.

The department of Precision Mechanics is responsible for the mechanical design, manufacturing and testing of these optical instruments.



*Figure 1.1: A test set-up*

For alignment of these optical systems and instruments TNO TPD has developed dedicated, monolithic, flexure-based alignment mechanisms.

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## 2. CONSIDERATIONS FOR ALIGNMENT AT SYSTEM LEVEL

An opto-mechanical system requires a certain accuracy and stability depending on the application, such as an opto-mechanical instrument for space or a breadboard set-up to demonstrate the principle of an optical design. The stability and accuracy requirements as well as the optical configuration of the system lead to a set of mechanical requirements. The critical degrees of freedom that need to be aligned are also determined from the optical design.

Accuracies required on the system cannot be achieved by manufacturing and assembly of components with which only an accuracy of about 1 mm is achievable. Therefore alignment is necessary.

The accuracy requirement is translated to requirements on resolution and stroke for the alignment mechanism. Passive systems are mostly considered since the introduction of active elements yield a more complex design. Furthermore, a passive system is vacuum compatible and the elements have no development of heat unlike most active systems. However, the absence of active control requires high stability of the system and hence of the alignment mechanisms.

Alignment mechanisms can be classified depending on their stability and alignment resolution as shown in Table 1.

alignment method	resolution	stability
off-the-shelf alignment mechanisms	low 1-10 $\mu\text{m}$ or 1-10 $\mu\text{rad}$	low > 100 nm or nrad per hour
shims	low 1-10 $\mu\text{m}$ or 1-10 $\mu\text{rad}$	high few nm or nrad per hour
monolithic alignment mechanisms with flexures and locking device	high 1 nm -1 $\mu\text{m}$ or 1 nrad -1 $\mu\text{rad}$	high few nm or nrad per hour

Table 1: classification of alignment mechanisms

For a resolution and a stability higher than given for dedicated alignment mechanisms in Table 1, active control is required.

A complete optical system can be built from a combination of specially designed alignment mechanisms and off-the-shelf products.

An independent adjustment needs to be obtained or at least a strongly converged adjustment procedure has to exist where independent degrees of freedom and their order of alignment need to be determined.

Nevertheless, the alignment of a complex system can be extremely difficult and can end up in an iterative time-consuming process. The shift in position during locking is therefore a vital parameter for alignment while little information is available. Attention to this subject will be given in the following section.

## 3. DESIGN PRINCIPLES AND GUIDELINES

A design can be made if requirements such as stroke, resolution and stability are defined for the relevant degrees of freedom.

A mechanism meeting high requirements on resolution and stability can be realized by a statically determined monolithic flexure-based design. A low-stress suspension and a predictable dynamical and thermal behavior can be achieved by a statically determined design while a monolithic design results in no play and no hysteresis in the mechanism. Stiff directions can be separated from non-stiff directions using elastically deformable elements. These elements are especially useful for a limited stroke or angle. They are realized by means of spark erosion.

To make a good design it is necessary to understand what factors influence the resolution and stability of the mechanism, such as thermal effects and hysteresis.

Friction and play of the mechanism and the actuator influence the resolution. Applying a preload can overcome play but will increase friction. The resolution of the mechanism is determined by the actuator stiffness and by the friction felt during manipulation of the component. The virtual play or position inaccuracy is given by:

$$S_v = \frac{2W}{c}, \quad (1)$$

where  $S_v$  is the virtual play,  $W$  the friction and  $c$  the actuator stiffness [1].

An adjustment screw as actuator can provide for a high resolution but does not provide for a very stable positioning. Lubricant in the screw thread of the adjustment screw can influence its stability as the lubricant creeps. Furthermore, an adjustment screw does not provide an unambiguous fixation for positioning.

From this it can be concluded that removal of the adjustment screw and use of a locking device to fix the position is mandatory to achieve high stability.

High resolution, high stability alignment mechanisms consist of an adjustment mechanism and a locking device.

The GAIA OPD angular fine alignment mechanism (Figure 3.1) demonstrates a design with flexure elements [2] [3]. It adjusts 2 rotations, with a 2-mrad stroke and a 1- $\mu$ rad resolution.

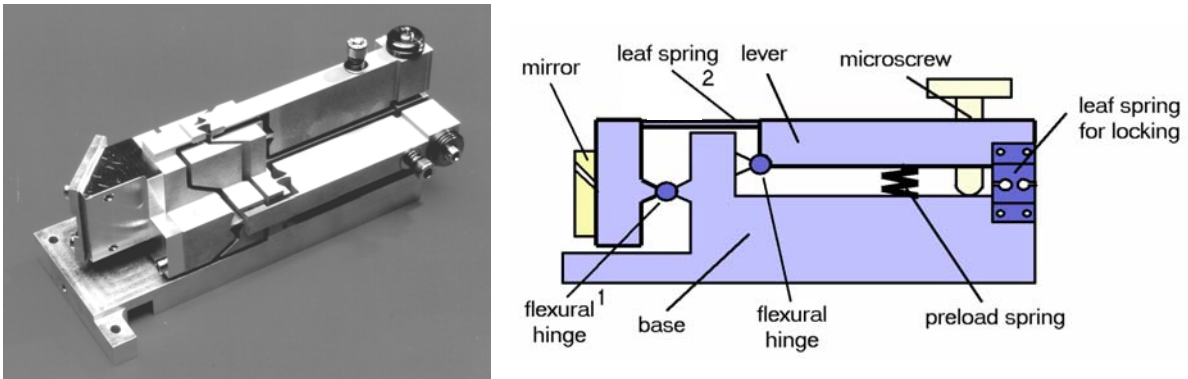


Figure 3.1 and 3.2: GAIA OPD monolithic angular fine alignment mechanism and schematic view of the mechanism

Figure 3.2 gives a schematic view of one of the rotation adjustment mechanisms. A flexural hinge (1) allows the mirror to rotate with respect to the base. Adjustment is made by means of a micrometer screw. The levers rotation is transferred to the mirror mount by means of a leaf spring (2).

The rotation mechanisms are orthogonally placed to provide independent adjustment. The complete mechanism consisting of levers, leaf springs, hinges and base, is made of one piece of Aluminum by means of spark erosion. Adjustment with a micro spindle provides sufficient high resolution, but insufficient stability. Therefore locking is required.

A releasable locking device is necessary because of the iterative character of aligning optical components. Figure 3.3 shows the locking for the GAIA mechanism.

Locking is done by means of clamping leaf springs. Only the relevant degrees of freedom are locked while others are non-stiff. Hereby the statically determined structure is maintained. In order to minimize the effect of a shift in position during locking two anti-torque leaf springs are implemented as well. After locking the micrometer screw is released to overcome the over-constrained degrees of freedom.

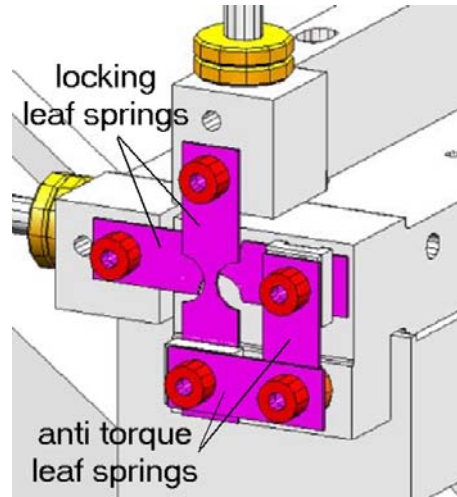


Figure 3.3: Locking of the GAIA-mechanism

A normal force is applied by means of a bolt. In an ideal clamping a pure normal force is applied, because other force components will lead to shift. Therefore, the introduction of a torque and possible transverse force during locking needs to be avoided or minimized. By tightening the bolt, a momentum is applied that must overcome the friction in the bolt's head and thread. An extra transverse force is applied using a spanner. By releasing the spanner, the sign of the friction inverts and thereby the elastic shaft of the bolt is forced to hold the friction momentum. By installing a plate that can absorb the introduced torque and transverse forces great improvement is made.

The mechanism can be subjected to environmental forces. After removal of any applied loads or an inhomogeneous temperature distribution, the mechanism has to reproduce its originally adjusted position. The design of the locking device can be optimized to achieve high reproducibility.

In a clamped joint, loads are being transferred by means of friction. The load is gradually transferred in the friction plane by means of a normal force. The normal force will lead to strain. Differences in stiffness will lead to strain differences. Load transfer will therefore lead to micro slip.

A hysteresis free clamping is improved by decreasing the length of the slip front in the direction of the degree of freedom that needs to be fixed (in the length direction of the constricted leaf springs in Figure 3.3). This can be realized by minimizing the contact area in this direction. However, a large normal force distribution is obtained due to a high contact pressure in the friction planes. This high contact pressure results in inevitably a transverse contraction and thereby in some shift in the clamping plane.

In the GAIA-mechanism an extra preload is necessary to overcome play in the adjustment screw. After locking and releasing the adjustment screw, the preload is transferred to the leaf spring. This force will give a reproducible elongation of this elastic element. Therefore limited preload should be applied. The elongation is highly reproducible and consistent with theoretical calculations, so a good compensation is possible.

Off-the-shelf stages need an hour or two before the mechanism has stabilized. In contrary, for dedicated alignment mechanisms the new position after locking is directly known because of the high stability of the locking.

## 4. APPLICATIONS OF ALIGNMENT MECHANISMS

### 4.1 Achromatic Phase Shifter

The “Achromatic Phase Shifting” (APS) test set up and Nulling breadboard have been developed for ESA by TNO TPD to demonstrate the feasibility of key techniques for the realization of the IRSI/Darwin mission [4] [5]. Darwin will use a flotilla of six space telescopes, each of which will be at least 1.5 meters in diameter. They will work together to scan the nearby Universe, looking for signs of life on Earth-like planets.

The APS breadboard (Figure 4.1) is developed to obtain a deep null by destructive interference, i.e. a nulling depth of about  $10^{-4}$  over the wavelength range of 530-750nm and to measure the actual phase difference between the two interfering beams as a function of wavelength.



Figure 4.1: APS breadboard

The alignment is done by means of alignment mechanisms, which are dedicated developments or standard components. The optical configuration has been guiding in the selection and design of these mechanisms. The heart of the optical configuration consists of an interferometer. In between the splitting beamsplitter and the recombining beamsplitter very high stability (nanometers) and very high alignment accuracies (sub-micrometer and sub-microradian) are required. Therefore all alignment mechanisms in between the splitting and re-combing beamsplitter are dedicated mechanisms. Most crucial in this respect are both pairs of 4 prisms. Accurate alignment and stable positioning is mandatory to achieve a stable and deep nulling depth.

#### Prism alignment mechanism

The prism alignment mechanism can adjust two rotations. Its specifications are:

stroke:	10mrad
resolution:	2 $\mu$ rad
stability:	2.2 $\mu$ rad per month around vertical axis 2 mrad per month around horizontal axis

Figure 4.2 presents the prism block alignment.

Maximum stability and alignment accuracy is required for this mechanism. It has glass prisms bonded on top of a monolithic aluminum block (100 mm high and 300 mm x 300 mm). The block is mounted iso-statically on top of a vibration-isolated table by means of three constricted leaf springs.

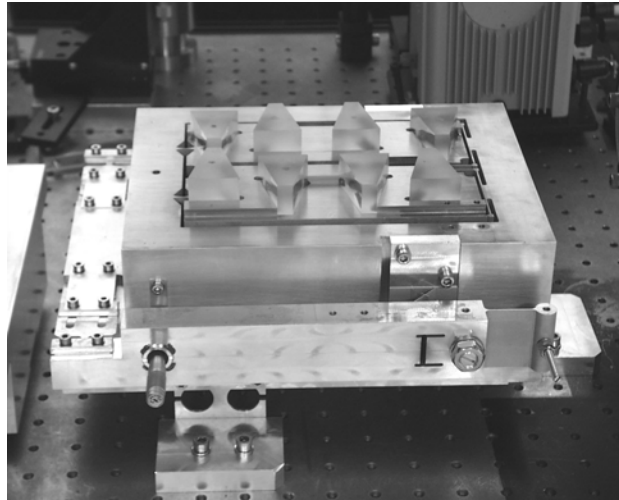


Figure 4.2: Prism block alignment mechanism

To be able to align both sets of prisms a mechanism has been spark eroded in the base block (Figure 4.3). Two bars form the base for both prism sets (four prisms on each bar). These bars are both suspended by a flexural hinge (designed for  $\pm 0.010$  rad) at the left side and two folded leaf springs at the opposite side. Folded leaf springs are elastic construction elements, which restrain one degree of freedom (translation perpendicular to paper), comparable to a thin flexible strut.

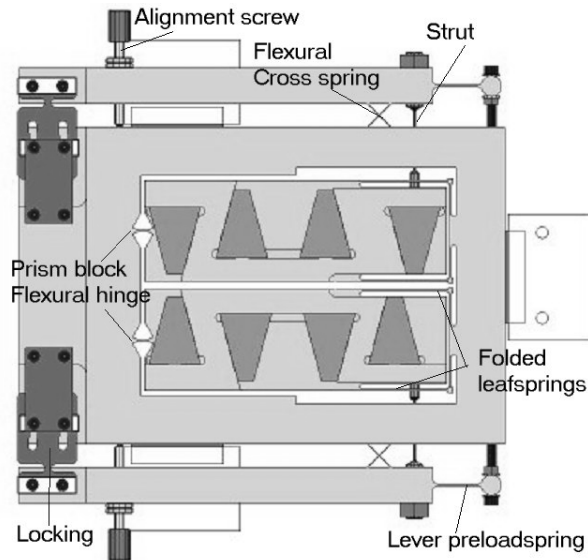
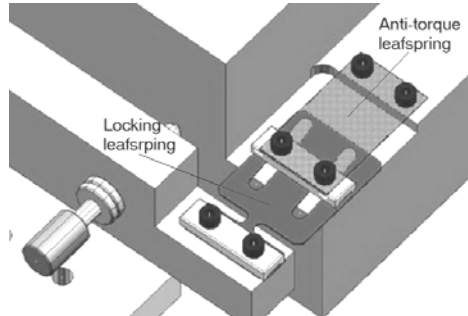


Figure 4.3: Top view of Prism block

Actuation of the bars is done by means of a micrometer screw mounted on a lever. The lever is mounted at the outer side of the frame and is suspended by a flexural cross spring hinge. Lever and flexure are made of one piece by means of spark erosion. These levers are mounted against the base block.

To avoid drift or creep after alignment there is a locking leaf spring implemented at the micrometer side of the lever (Figure 4.4). The lever realizes a reduction ratio necessary to achieve sufficient accuracy and to reduce drift during locking. The connection between lever and inner rotating base with the prisms pairs of the APS is done by means of a strut protruding the outer rectangular frame (Figure 4.5).



*Figure 4.4: Locking leaf spring for lever alignment with anti-torque provision for locking screws*



*Figure 4.5: Reinforced strut for prism block alignment*

The flexural cross spring hinge of the lever is able to rotate approximately  $\pm 0.17$  rad. At the other end of the lever there is a leaf spring used to pre-load the lever which is necessary to achieve the full rotation of the lever.

#### **4.2 Nulling**

Comparable to the APS test set up the Multi Aperture Imaging Interferometer or “Nulling breadboard” has been developed for ESA by TNO TPD to demonstrate the feasibility of key techniques for the realization of the IRSI/Darwin mission [4] [5]. The main objective of the Nulling breadboard is the demonstration of feasibility of deep nulling of a point source as well as of imaging an extended source.

The alignment approach is comparable to the approach used in the APS breadboard. Again all the components in between the splitting and recombining beamsplitters have very high stability requirements. The other components (“black colored” mechanisms in Figure 4.6) have less high stability requirements and are therefore standard components.





Figure 4.6: Nulling breadboard

Two dedicated alignment mechanisms for two rotations will be presented. These mechanisms have high stability requirements (nanometers during measurement) and require relatively low-resolution alignment accuracies (mrad stroke).

#### **Prism rotation mechanism**

Two pairs of beams above each other have to be reflected under a 90-degree angle. Therefore two prisms have been implemented in the design. These prisms have to be aligned in the mrad stroke. After the alignment the prisms have to be locked due to the high stability requirement.

The prism rotation mechanism adjusts two rotations, one around the vertical axis and one around the horizontal axis parallel to the incoming beam. The specifications are:

stroke:	$\pm 3^\circ$ around vertical axis
	$\pm 2^\circ$ around horizontal axis
resolution:	1mrad
stability:	2.6 $\mu$ rad per month

The top half of the mechanism (Figure 4.7) rotates around a vertical pin mounted in the bottom part. Manipulation is realized by the horizontal alignment screw. After alignment the stability is guaranteed by mounting the top part at three places to the bottom part. The horizontal hinge is a flexural hinge. Due to a lack of space, the hinge is placed at the side of the mechanism instead of the middle. The lever is equipped with a stop to prevent the flexible hinge from too high bend stresses (aside the locking leaf spring in Figure 4.8). Part of the flexible hinge material has been removed to reduce the rotational stiffness and thereby limit the force needed to bend the hinge down.

After alignment the mechanism is locked (see back view) by means of a restrained leaf spring.

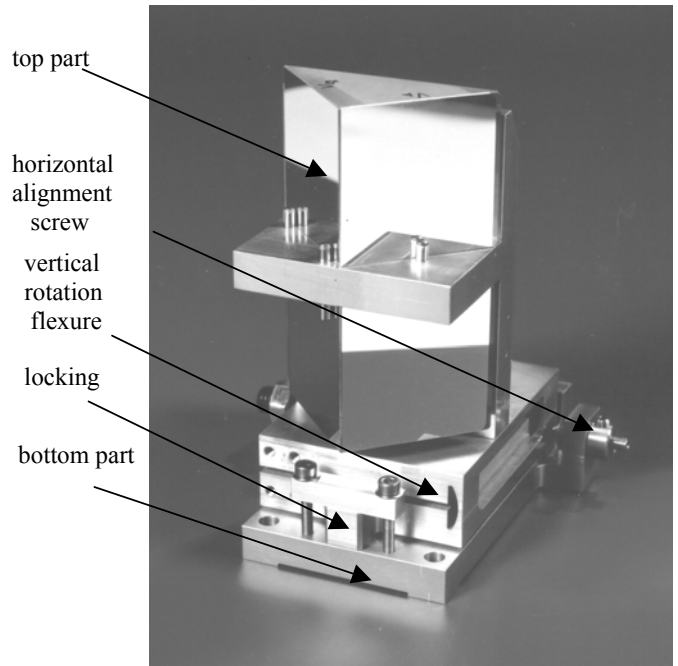


Figure 4.7: Front view of the prism rotation mechanism

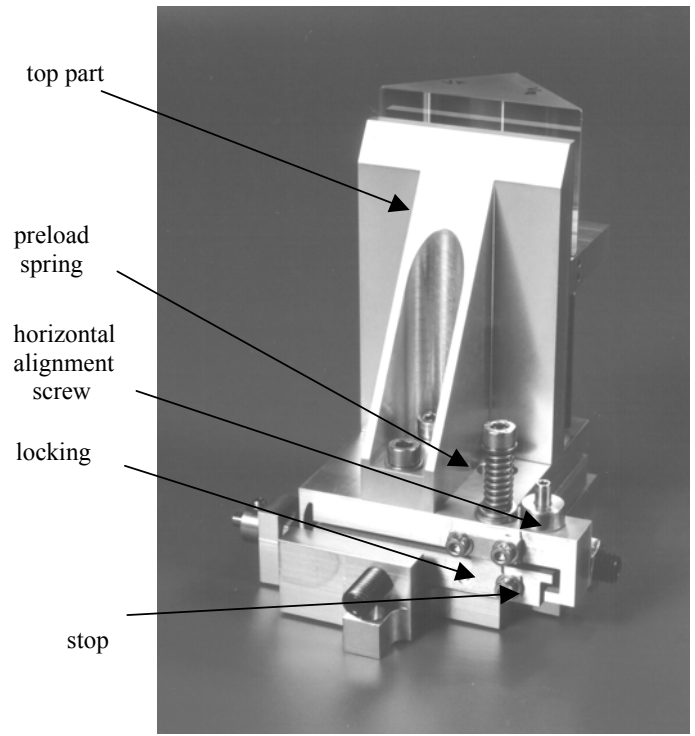


Figure 4.8: Back view of the Prism rotation mechanism

### Retro reflector translation/rotation base

The retro reflector adjusts two rotations and one translation.

The specifications are:

stroke:	$\pm 2^\circ$	$\pm 5\text{mm}$
resolution:	1mrad	0.5 mm
stability:	2.6 $\mu\text{rad}$ per month	10 $\mu\text{m}$ per month

The retro reflector holds the two mirror elements. The holder is machined as a single entity to ensure that the best tolerances possible can be obtained. The base of the mechanism allows 2 rotations, which are both in the horizontal plane.

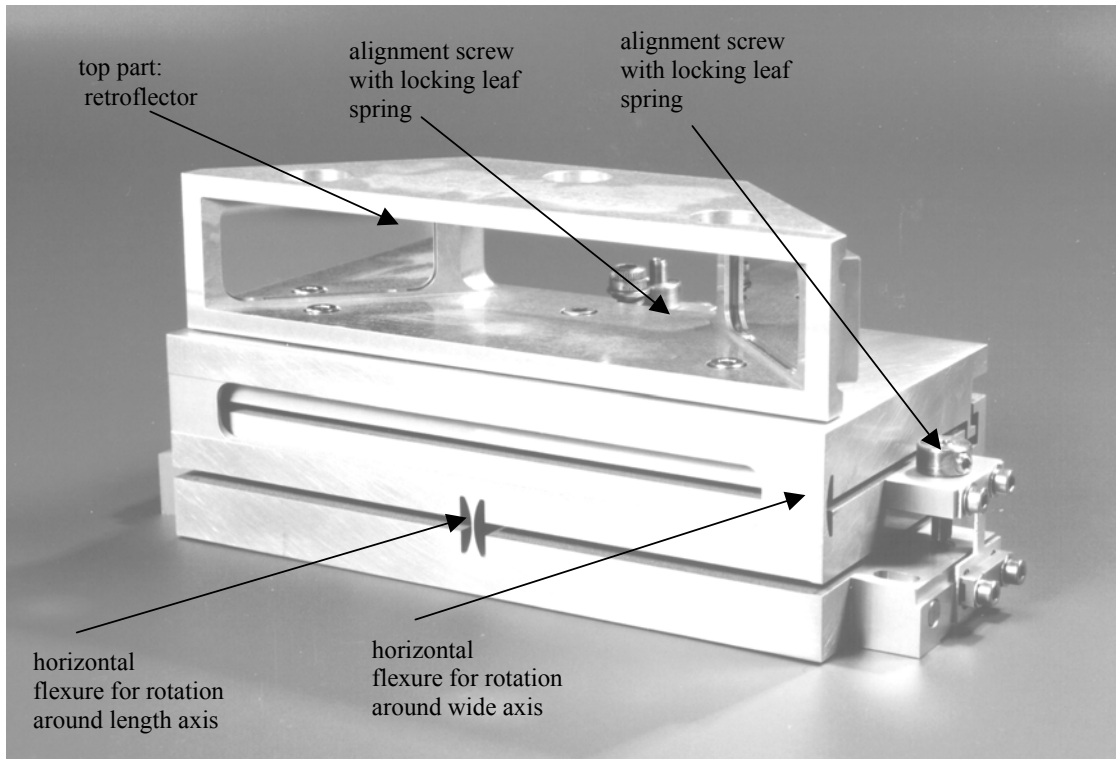


Figure 4.9: Retro reflector mechanism.

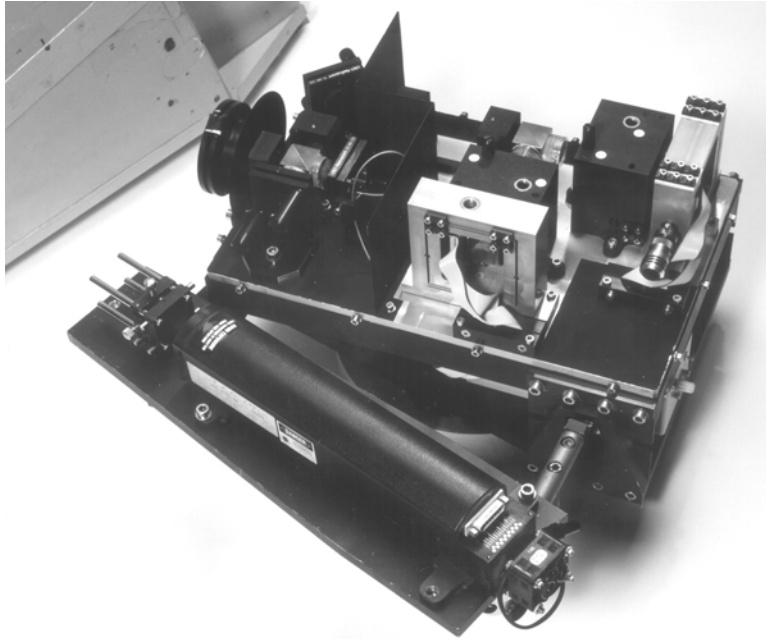
The translation does not require a very high accurate alignment therefore it is realized by sliding the mechanism along a rail, which is mounted on the Nulling breadboard. The alignment screw (not shown in Figure 4.9) is mounted on the breadboard. After alignment the mechanism is fixed onto the breadboard (with three screws).

Both rotations are realized by two flexures, which are implemented in the base of the mechanism by means of a flexural hinge. Part of the material of the flexural hinge for rotation around the wide axis has been removed along this rotational axis (Figure 4.9). By doing so, the rotational stiffness of the hinge is reduced to minimize the force on the alignment screw.

To limit the stroke this flexure has a stop at the backside of the mechanism. Locking leaf springs are implemented for both rotations.

### 4.3 Shearography interferometer

TNO TPD developed in collaboration with Delft University of Technology and the European Aerospace industry a shearography interferometer (Figure 4.10) to detect de-lamination of CFRP body panels for airplanes. Stability was an important issue not only because of the high stability requirements of the instrument itself but also because of robustness. The instrument should be stable enough to be used in laboratory circumstances as well as “in- the-field” at different airfields and aerospace plants.



*Figure 4.10: Shearography test set up.*

#### **Rotational alignment of a Safart element**

The specifications for the Safart element adjusting two rotations are:

stroke:	$\pm 2^\circ$
resolution:	1 mrad

A Safart element is a rectangular optical element from Quartz (Figure 4.11).

This element is mounted in the middle of the mechanism. It is preloaded against several well-defined small contact areas.

At the top of the mechanism a flexural hinge for rotational around the length axis of the Safart element is realized (‘along Safart axis’). The left screw in Figure 4.11 is used for adjustment of this rotational degree of freedom. After adjustment this alignment is locked by means of a leaf spring that is placed between the middle part that contains the Safart element, and the outer part where screws are placed to fix the spring leaf (only holes are visible in Figure 4.11).

The other rotation is realized by a flexure at the bottom of the mechanism (‘perpendicular to Safart axis’). The right micrometer screw in Figure 4.11 adjusts this degree of freedom. The screw is elongated to be able to protrude through the middle part of the mechanism containing the Safart element. The locking leaf spring for this rotation can be seen left at the bottom of the mechanism.

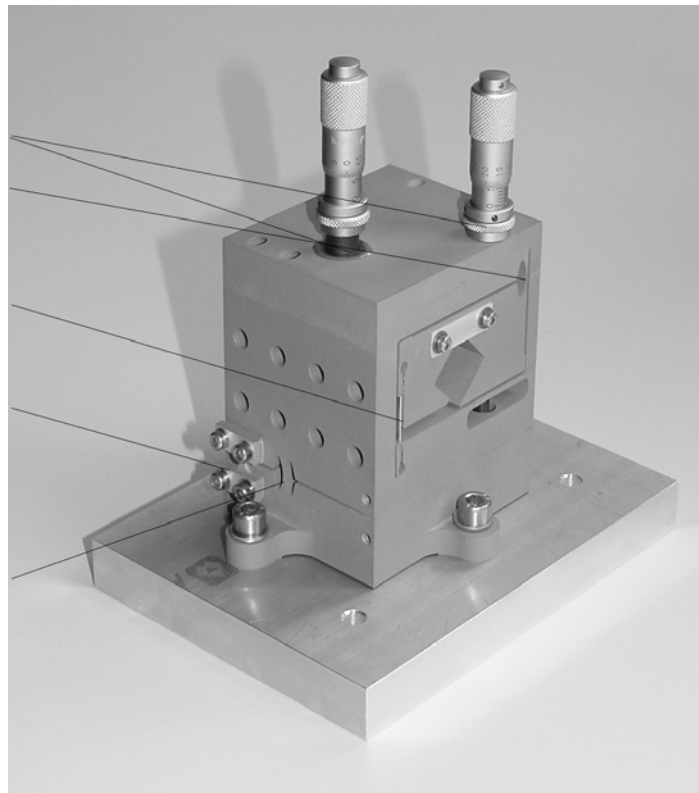
alignment screws

flexure for  
rotation along  
Safart axis

locking  
leaf spring  
along Safart axis

locking  
leaf spring  
perpendicular  
to Safart axis

flexure for  
rotation  
perpendicular  
to Safart axis



*Figure 4.11: Alignment mechanism of Safart element.*

## 5. ONGOING RESEARCH

An ongoing research program has the objective to improve the alignment mechanisms continuously. In addition to theoretical principles this program is focused on practical design guidelines.

The topics of this project are:

- Improvement of existing mechanisms as well as design and development of innovative alignment mechanisms
- Design, development and testing of low-shift locking devices
- Design of modular alignment mechanisms
- Qualification of alignment mechanisms including measurements on stability and shift during locking

### Design and development of alignment mechanisms

By analogy of optical systems the most occurring degrees of freedom are two rotations or three translations. New mechanisms are designed to adjust these degrees of freedom. A newly developed locking device is integrated in this design.

Furthermore, the performance of existing mechanisms is optimised by redesign. Some high resolution ( $< 100$  nm), high stability ( $< 50$  nm/week) flexure-based alignment mechanisms are available at the moment.

### Design, development and testing of low-shift locking devices

Last year a test set-up has been built to carry out measurements on the shift during locking. After adjustment of a flexural hinge this shift has been measured by locking a leaf spring. The set-up was tested under different preloads. Capacitive sensors were used for measuring the shift. Many different locking devices have been examined. Measurements have been carried out to determine e.g. the influence of using lubricant for the locking screw, the order of turning the locking screws, geometry of contact surface and polishing this surfaces.



*Figure 5.1: a test set-up used during the research program*

Clamping joints were further improved. Hereby obtaining extreme low shift and drift. According to measurements using a new locking device to lock a leaf spring that locks a flexural hinge, a shift in position during locking is minimized ( $< 50$  nm) while the mechanism is highly stable after locking ( $< 50$  nm/week).

### Design of modular alignment mechanisms

The development of a low-shift and high-stability locking device is the first step into development of a new, more universal opto-mechanical alignment system. For such a mechanism it will be possible to remove the actuator and the manipulator so that the component will remain placed on a coupling device as shown in Figure 5.2. Removal of the mechanism after alignment will save space and will make the alignment mechanism available for reuse ('light colored' parts can be removed). The possibilities of a modular alignment mechanism are examined this year.

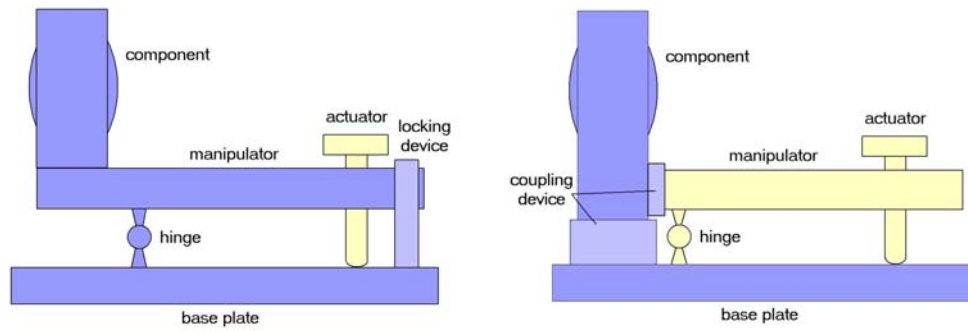


Figure 5.2: schematic view of an alignment mechanism with locking device left and modular part right

### Qualification of alignment mechanisms

Stability and 'shift' is hardly ever specified for off-the-shelf mechanisms. As part of the research program a measurement system for qualification is built to be able to measure the shift and stability of alignment mechanisms in the future.

A six degrees of freedom measurement system using capacitive sensors with nanometer resolution is developed using a low-noise level detector and highly stable electronics.

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