An adjustment for five degrees of freedom as an alternative for a hexapod mechanism

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ABSTRACT

In modern mirror optics often consists of a limited number of elements, in which many aberrations may be attacked by adjusting only one element in five degrees of freedom, i.e. all degrees of freedom except the rotation around the optical axis. When the adjustment has to be reusable and mass and stiffness are of importance, a hexapod mechanism is an 'the mechanism of choice' for this function. This choice holds even though the hexapod controls six degrees of freedom, while control of only five degrees of freedom is required, simply because there was no known configuration that does only control the required five degrees of freedom while maintaining the superior mass and stiffness properties of the hexapod.
In this paper a mechanical configuration is presented that offers a worthwhile alternative for the simultaneous adjustment of five degrees of freedom (one rotation constrained), in the sense that:

- The rotation around one axis is constrained by the mechanical configuration, meaning that only the required five degrees of freedom have to be controlled. This means only five instead of six actuators are needed, which results in an increase in reliability.
- The mass and stiffness of the mechanism are comparable with the hexapod.
- From a mechanical and control point of view the configuration is less complex than the hexapod.

Keywords: Opto-mechanics, hexapod, constraint of rotation

1. INTRODUCTION

The request for high performance mirror optics has impact on the design, the quality of the mirror elements and the position of the mirror elements. In order to maintain a high performance in an environment where positions may drift, the integration of a mechanism that re-adjust positions is required. Such a mechanism will have to control several degrees of freedom in order to compensate for the possible drifts in the optics. However, since most imaging optical systems are characterized by an optical axis, one will generally find that rotation around (or near) this axis has no (or negligible) effect on the performance, so control of this rotational degree of freedom in imaging optics is not required.

An example of this can be found in the system design of the astrometer in the GAIA mission of ESA. The aim of the GAIA mission is to provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars, combined with astrophysical information for each star [1]. An exploded view of the GAIA satellite is given in Figure 1.
The astrometer is the instrument that will serve to determine star positions with micro-arcsecond accuracy. It contains a telescope with mirror optics. Due to various reasons the initial alignment of the telescope may be lost after launch (vibration loads during launch, gravity release). In the optical analysis it has been determined that aberrations due to this drift in mirror positions may be corrected by adjusting the position of the second mirror in five degrees of freedom, i.e. all degrees of freedom except the rotation around the axis normal to the plane of the mirror. Figure 2 shows the optical path in the telescope and the position of the adjustment mechanism.
The application in a satellite also means that strict requirements exist in the fields of reliability, mass (<5 kg including actuators, sensors and locking mechanism) and stiffness (lowest resonance frequency > 200 Hz in locked mode).

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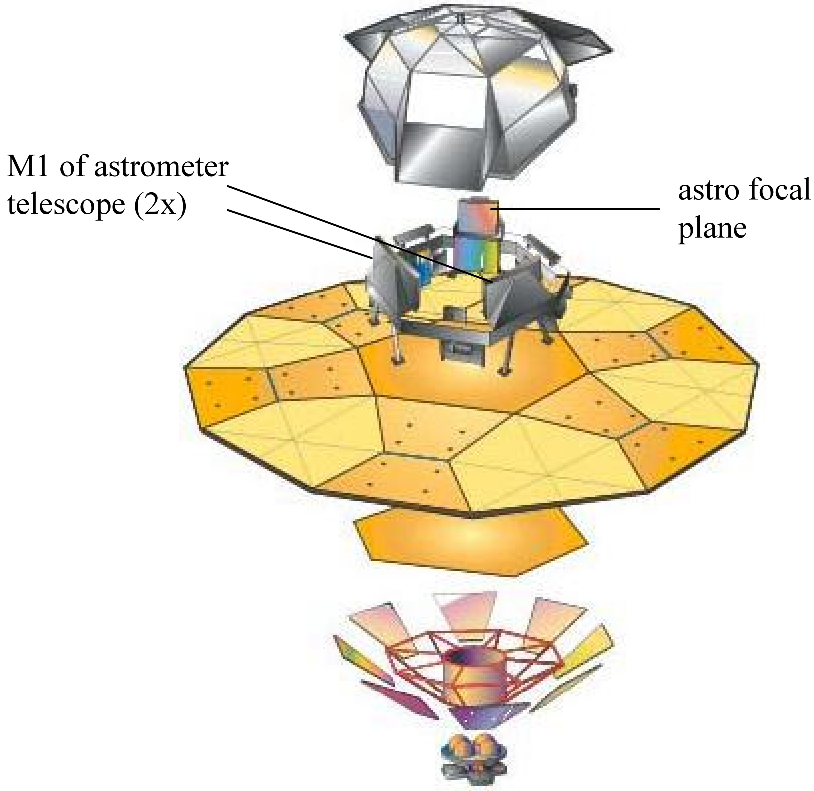

Figure 1: Exploded view of the GAIA satellite (ESA)

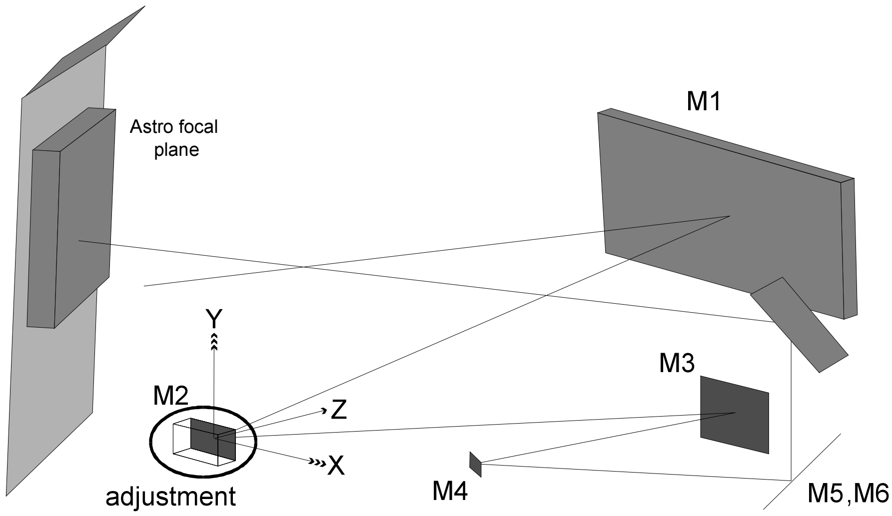

Figure 2 : Optical path in the telescope of the GAIA astrometer, the position of the five DoF adjustement is encircled. Rotation around z does not have to be adjusted (ref [1]).

2. CONFIGURATION OF THE MECHANISM

1. Requirements

The requirements for the adjustment mechanism to be used in the astrometer are:

- The mechanism shall be adjustable in 5 DoF, translations along X, Y and Z and rotations around X and Y (Defining a reference, orthogonal trihedral XYZ in the mirror, with 'XY' parallel to base and 'Z' towards mirror interface)
- The ranges are ±150 μm for the translations and ±2 mrad for the rotations
- Volume of 260 mm x 110 mm x 130 mm, mechanism to be placed behind the mirror.

In a preliminary study it was already suggested that a hexapod mechanism would be the proper choice for the mechanism [2]. This configuration allows adjustment of all six degrees of freedom and has advantages in the field of mass and stiffness. Moreover, the configuration fits nicely behind a mirror. The use of the hexapod configuration as an adjustment mechanism has already been used for the secondary mirror of earth bound telescopes, see for example [3].
Summarized the advantages of the hexapod mechanism are:

- The hexapod has superior mass and stiffness properties.
- The hexapod mechanism has reached technological maturity, they have reached the level of commercially available product, see [4].

However, the disadvantages for the given function are:

- The hexapod controls six degrees of freedom, while control of only five degrees of freedom is required. In principle the function could be achieve with one actuator less.
- The development of a new, dedicated hexapod is a major task, due to the mechanical and the control complexity. Various publications dedicated to the presentation of control solutions elaborate on the problems that are present [5, 6].

Especially the fact that the hexapod solution required six actuators and asked for control of six degrees of freedom while, at least in principle, five actuators and control of five of degrees of freedom should suffice was unsatisfactory. For this reason the search was open for a kinematically true five DoF alternative.

2. The five DoF concept

The search for an alternative for the hexapod was performed along the lines of fundamental kinematics, in which the degrees of freedom are restricted by theoretical links, that each restrict only one (translational) DoF (such links can easily be translated to physical entities).
Using such links, a body can be restricted in all degrees of freedom by a properly placed set of six links. Figure 3 shows two correct configurations, an orthogonal configuration and the hexapod configuration. By adding actuators to all the links, the body can be made adjustable in six degrees of freedom.

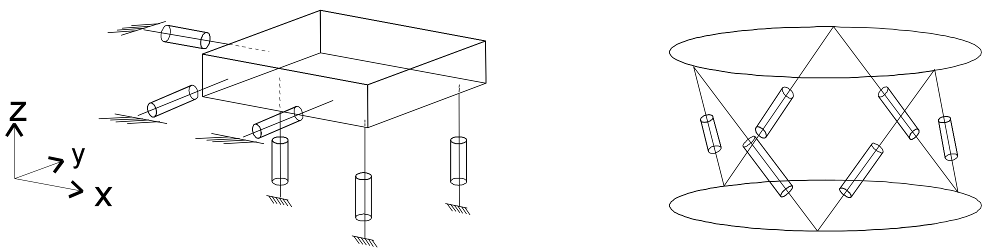

Figure 3: Orthogonal and hexapod configuration for a body adjustable in 6 DoF

In the above configurations it is not possible to restrict one rotational degree of freedom by simply removing one actuator. When one rotational degree of freedom has to be restricted, it is found that an additional body is always required. Figure 4 depicts the basic example, ref [7].

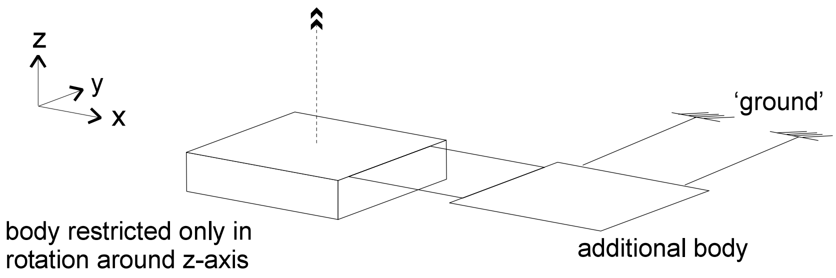

Figure 4: Principle of a body restricted in on rotation

The presence of the additional body makes this option less attractive at first sight, especially since the additional body has its own, unrestricted degrees of freedom. Nevertheless, the idea of a five DoF mechanism with an additional body was pursued.

This resulted in a mechanism concept as sketched in Figure 5. In the left side of the figure the configuration is given without actuators, on the right side a simple orthogonal set of actuators is shown.

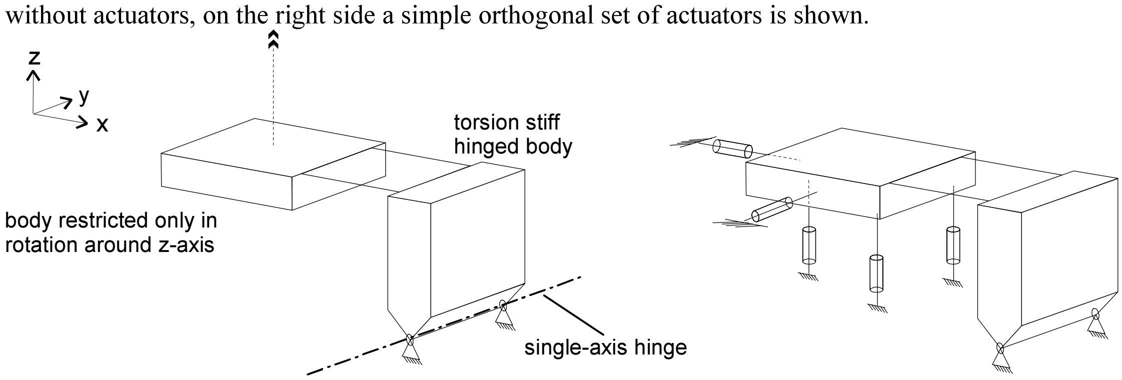

Figure 5: Alternative configuration to create a body where rotation around z is restricted, without and with a set of adjustable links.

The way the adjustable links are placed in Figure 5 conflicts with the box volume specified in the main requirements. However, the set of adjustable links for x and y can be rotated 45° without adding any cross-coupling. Another possibility is having one of the actuators acting on the additional body. In order to keep the y-actuator within the limited y-dimension its attachment point shall be shifted along the body. These configurations are in given in Figure 6.

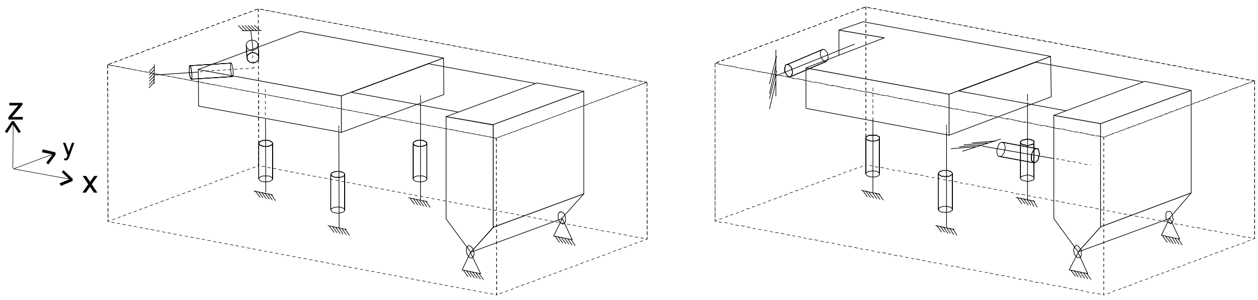

Figure 6: Two variations on the 5 DoF mechanism, with modified adjustable link configuration, to fit in box volume

3. Rigid body simulation

According to kinematic theory the FM-configuration should work as intended. In order to convince both our colleagues and ourselves, a kinematic simulation was made based on rigid models. A screen copy of the model is given in Figure 7. In this way it was verified that all five free degrees of freedom could be actuated as designed, while the rotation around the vertical axis remained fixed.

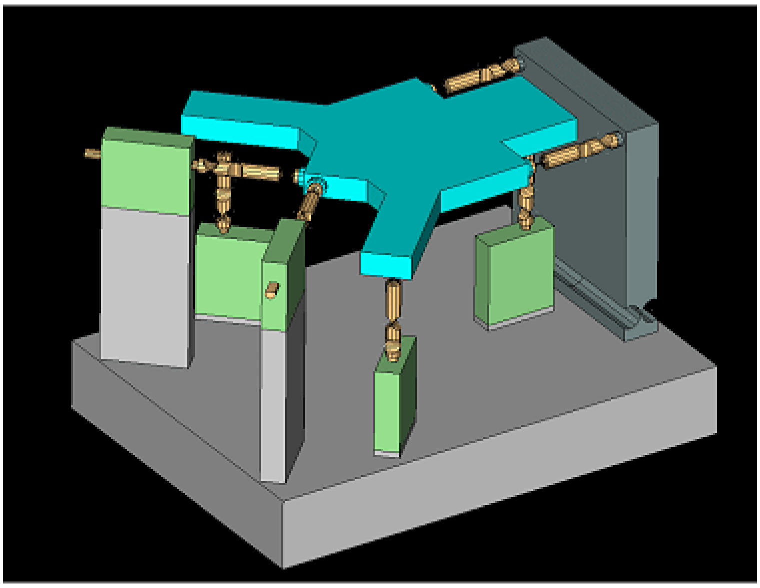

Figure 7: Rigid body model of 5 DoF mechanism. Green blocks indicate actuators.

4. Comparison with hexapod configuration

The table below several properties of the hexapod and the new configuration are compared, with a subjective scoring, as prepared for the proposed adjustment mechanism.

Table 1: Comparison of hexapod and new configuration for the described functionality.

Property	Hexapod	5 DoF	Comment
Volume	+	+	The configuration of the hexapod is more compact, but the additional space required by the 5 DoF mechanism uses the rectangular space that is available for M2
Volume for internal systems	+/-	+	The compactness of the hexapod is also its disadvantage. Since the pivots of the links are placed pairwise near to each other, the volume for actuator systems is small. There are possibilities to create more space for the actuator systems, but this at the cost of either volume or stiffness. In the 5 DoF mechanism the attachment points of the links are further apart.
Stiffness	++	+	In a properly dimensioned hexapod, the stiffness of each DoF is higher than the stiffness of a single link (in the optimal configuration the stiffness associated with one axis is equal to the stiffness of two links [8]) In the 5 DoF mechanism the stiffness for the x- and the y-direction is equal to that of one link.
Reliability	+/-	+	Each adjustment will require an actuator system, which is regarded as a critical system with respect to reliability. Adding a DOF that requires an actuator system increases the change of failure with 20%.
Mechanical complexity	+/-	+	Complexity of the 5 DoF mechanism is estimated smaller, the hexapod requires design and manufacture of a system with many different local co-ordinate systems
Control complexity	+/-	+	The hexapod has the extra burden of cross-coupling between axes, and the associated complexity of the control. In the 5 DoF, only parasitic movements -which can be characterized by simple goniometric relations- have to be compensated for.

It is found that the new configuration discriminates itself by improved reliability and low complexity, while the penalty is small. Wherever the described 5 DoF adjustment is required and reliability is a top issue, the new configuration is a serious contender when compared to the hexapod mechanism. For this reason the 5 DoF mechanism is proposed to serve as an adjustment mechanism in the astrometer of the GAIA mission.

3. CONCLUSIONS

The presented mechanical configuration can serve as five degrees of freedom, reusable adjustment.

When compared with the hexapod mechanism, it is found that -for the case where one rotation has to be constrained- the presented adjustment mechanism has:

- higher reliability (based on the need of one actuator less)
- lower mechanical and control complexity

while the penalty in terms of mass and stiffness is low.

As such the presented mechanism could replace the hexapod mechanism as the preferred choice when a five DoF adjustment mechanism has to be developed.
Mainly based on the increased reliability, the new mechanical configuration has been proposed to serve as a adjustment mechanism in the astrometer which will be part of the GAIA mission of ESA.

ACKNOWLEDGEMENTS

The idea of the presented mechanism evolved in a discussion with Pieter Kappelhof. Afterwards we haven't been able to establish whether he or I came up with the solution.

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