

# DEPLOYABLE HEXAPOD USING TAPE-SPRINGS

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## RESUME :

Dans le proche avenir des systèmes d'observation spatiaux, apparaissent de nouveaux défis technologiques tels que la conception de systèmes multi-pupille volant en formation ou de systèmes extrêmement haute résolution (EHR) de très grande dimension et de haute agilité. Pour pouvoir relever ces défis, le département Recherche d'Alcatel Space étudie des concepts structuraux innovants pour les futures missions d'observation

Un de ces concepts repose sur un hexapode dont les jambes sont constituées de mètres-rubans enroulables. Cet hexapode est gerbé dans une configuration favorable durant le tir et se déploie de manière autonome une fois à poste. Les incertitudes de déploiement et les instabilités long-terme peuvent être corrigées au moyen d'actionneurs verticaux placés sous les pieds de l'hexapode et la pleine performance de l'instrument est atteinte au moyen d'optique active. Les avantages de ce concept par rapport aux structures hyperstables classiques sont :

- Une forte réduction de volume dans la configuration de tir autorisant la conception de systèmes de grandes dimensions,
- Une très forte relaxation des exigences de stabilité durant le tir grâce aux actionneurs et à l'optique active qui corrigeront les instabilités de la structure durant la mission. Ceci permet de ne plus dimensionner les structures que pour la vie orbitale et de concevoir des systèmes très légers en matériaux classiques : composites ou métaux.
- Un gain de masse et d'inertie augmentant l'agilité du système.

Ce concept est actuellement étudié avec le soutien de *l'Innovative Triangle Initiative* de l'ESA. Le but de cette étude est de développer et construire un démonstrateur d'hexapode reposant sur ce concept et d'évaluer sa reproductibilité de déploiement et ses capacités de correction.

Cet article présente l'algorithme de design optimal fondé sur l'analyse par intervalles qui a été utilisé pour définir la géométrie d'une maquette maximisant les capacités de correction et assurant l'espace de travail. Puis, la conception de la structure et les mécanismes d'enroulement des mètres-rubans sont décrits. L'article se conclut sur les résultats des essais de déploiement et de correction.

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## ABSTRACT :

In the near future of space observation systems, several technical challenges come into light like multi-pupil systems conceived as free flyers or extremely high resolution (EHR) systems with large dimensions and high agility requirements. To be able to face these challenges, the Alcatel Space Research Department is studying innovative structural concepts for future observation instruments.

One of these concepts is based on an hexapod whose legs are deployable coiled tape-springs. This hexapod is stowed in a favourable mechanical configuration for launch and self-

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deployed once in orbit. The deployment errors and long-term instabilities can be corrected thanks to six actuators located under the feet of the hexapod and the final optical performance is reached thanks to adaptive optics. The main advantages of this concept compared to classical hyper-stable telescope structures are:

- a reduced volume during launch allowing large systems design,
- a very strong reduction of dimensional stability requirements during launch thanks to the actuators and the adaptive optics which will correct the geometric instabilities of the structure after deployment. This allows to build very light structures sized only by orbital life with quite classical CFRP or metallic materials.
- a mass and inertia reduction which leads to an agility gain of the system.

This concept is currently examined with ESA Innovative Triangle Initiative support. The goal of this study is to develop and build a representative breadboard of an hexapod using this technology and to evaluate its deployment precision and correction capabilities.

This paper presents the optimal design algorithm based on interval analysis and used to define the geometry of the breadboard in order to maximise its correction capabilities and to insure its workspace. Then, the structure design and the 6 tape-spring mechanisms are described. The paper ends with the results of the deployment and correction tests.

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## 1 - INTRODUCTION

In the close future of space observation systems, many challenges come into light like multi-pupils systems conceived as free flyers or Extremely High Resolution systems with very large dimensions and high agility requirements. To be able to face these challenges, the Alcatel Space Research Department is studying innovative structural concepts for future observation instruments.

Adaptive optics, which should be used to correct an in-orbit instrument, seems to be unavoidable to improve nowadays solutions. If this is true, it should also be capable of correcting the positioning uncertainties of a deployment. For this, one must be sure that this optical technique is able to work after a deployment, this means that the passive part of the instrument is precise enough to allow picture shooting. A way to insure this precision is to use an active structure capable of roughly correcting its geometry.

The main advantages of a deployable and active telescope structure compared to classical hyperstable telescope structures are a reduced volume during launch allowing large systems design, a very strong reduction of dimensional stability requirements during launch as the geometric instabilities of the structure after deployment will be corrected and a strong mass and inertia reduction which leads to an agility gain of the system. This concept is currently examined by Alcatel Space Research Department with support of ESA Innovative Triangle Initiative in a study aiming at developing and characterising a breadboard of a deployable hexapod using tape-springs.

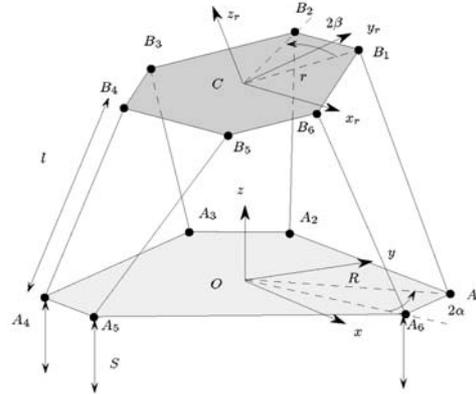
The following chapters will present how the geometry has been defined. The design of the breadboard will be described and this article will end with the results of the deployment and correction tests performed on the breadboard.

## 2 - OPTIMAL DESIGN

### 2.1 - PARALLEL STRUCTURES

The structure has been identified during a trade-off at the beginning of the project and is known as "active wrist" [5]. This structure (Figure 1) has 6 fixed-length legs that support the secondary mirror, each one being attached to the secondary mirror by a ball-and-socket joint and to the base by a U-joint. A linear actuator allows to move vertically the  $M_i$  point and to

control the secondary mirror position along 6 degrees of freedom. Such a structure is known in the field of mechanism theory as a *parallel structure*. Parallel manipulators have many advantages such as higher stiffness, better positioning accuracy, high speed and high load capacity. But one of their drawbacks is that their performances heavily depend on their geometry. So optimal design has become a key issue for their development and many researchers have recently paid attention to this [1],[2],[3],[4],[6],[7].



**Figure 1 : The design parameters of the structure**

In the first steps of this study, we developed an optimal design methodology allowing to determine almost all the possible geometries satisfying the two primary requirements: workspace and accuracy. The proposed methodology uses *interval analysis* which is a simple mathematical method that can provide lower and upper bounds for a function with interval unknowns. The *interval evaluation* of a function determines an interval that guarantees to include the exact lower and upper bounds of this function. Nevertheless the interesting point in interval analysis is that with a few operations we may determine easily a lower and upper bound of an arbitrary function when the variables are restricted to lie within some ranges.

## 2.2 - DESIGN PARAMETERS AND THEIR BOUNDS

The joint centres are located on circles and are symmetrical with respect to three lines located  $120^\circ$  apart. So, the geometry is defined by six design parameters:  $R$  and  $r$  the radii of the base and platform circles,  $\alpha$  and  $\beta$  the half angles between adjacent attachment points on the base and platform,  $s$  the stroke of the actuator,  $l$  the length of the legs. An analysis of the constraints on the deployable structure allows to determine that the values of all the design parameters are constrained and one can define ranges for these parameters.

## 2.3 - PRINCIPLE OF THE OPTIMAL DESIGN METHODOLOGY

The *allowed parameter box* (APB) is defined as a  $n$ -dimension box that contains all the allowable values of the design parameters. The first problem to solve is to consider one of the primary design criteria and to determine a set of boxes included in the APB such that for any design parameter value that lies within a given box of this set, the primary design criterion is fulfilled. Such boxes named *feasible parameter boxes* (FPBs) are defined as boxes and their union will be an approximation of the region that represents all the mechanisms satisfying one of the compulsory requirements. In our approach, FPBs are determined by using interval analysis. Hence the calculation of the intersection of the FPBs is trivial.

## 2.4 - CALCULATION

The aim of this calculation is to define the geometry of a breadboard whose height is about 500 mm and whose 6D workspace is defined by a simultaneous translation capability of  $\pm 2$  mm on each axis,  $\pm 2^\circ$  around X and Y axes and  $\pm 3^\circ$  around Z. The optimal design has been

performed with the following design parameters ranges :  $R \in [250 \text{ mm} ; 255 \text{ mm}]$ ,  $r \in [70 \text{ mm} ; 73 \text{ mm}]$ ,  $\alpha \in [10^\circ ; 20^\circ]$ ,  $\beta \in [10^\circ ; 20^\circ]$  and  $s \in [13 \text{ mm} ; 16 \text{ mm}]$ .

Solutions were found satisfying the requirements and optimising workspace and precision. The secondary criterion observed is the structure stiffness. For this, different solutions have been modelled thanks to finite element code NASTRAN and their stiffnesses have been computed. Among the set of solutions, we finally chose the best compromise between the maximal errors on X and Y and the overall stiffness.

### 3 - DEPLOYMENT CONCEPT

For launch, the structure is compacted thanks to 6 legs made with tape-springs. The M2 mirror is stowed by a mechanism which withstands the major part of the vibration loads without any strong dimensional requirement.

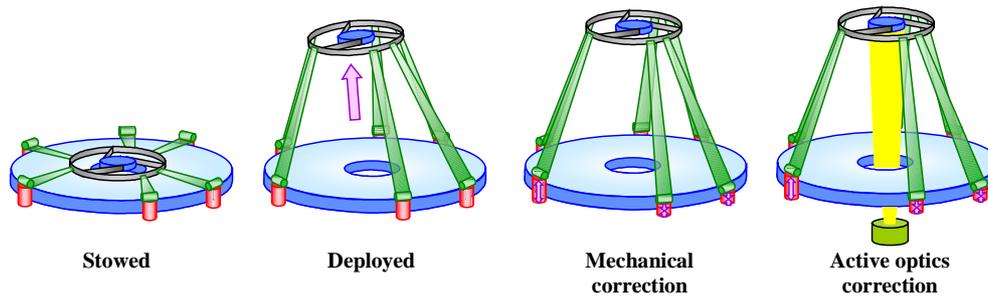


Figure 2 : Deployment stages

Once in operational orbit, the stowing mechanism is released and the 6 legs autonomously reach their full length configuration bringing the M2 mirror from the stowing point to a deployed point defined by the final length of the 6 legs and by the structure geometrical and mechanical defects. After deployment, the 6 vertical actuators can be used to compensate for deployment errors that can be measured thanks to a dedicated measuring system.

The structure then allows the acquisition of images. Even if their quality is poor, it is sufficient to use adaptive optics which then allows to reach the full performance of the system.

### 4 - BREADBOARD

The 6 tape-spring mechanisms used on the breadboard have been developed and manufactured by IWF TÜ Braunschweig who already applied them to motorised applications. The steel tape-spring can be rolled in the coiling mechanism. This mechanism has an internal coil spring which allows the self-deployment when the locking is released. For our breadboard, the 6 tape-spring mechanisms have all been tuned to deploy the same length.

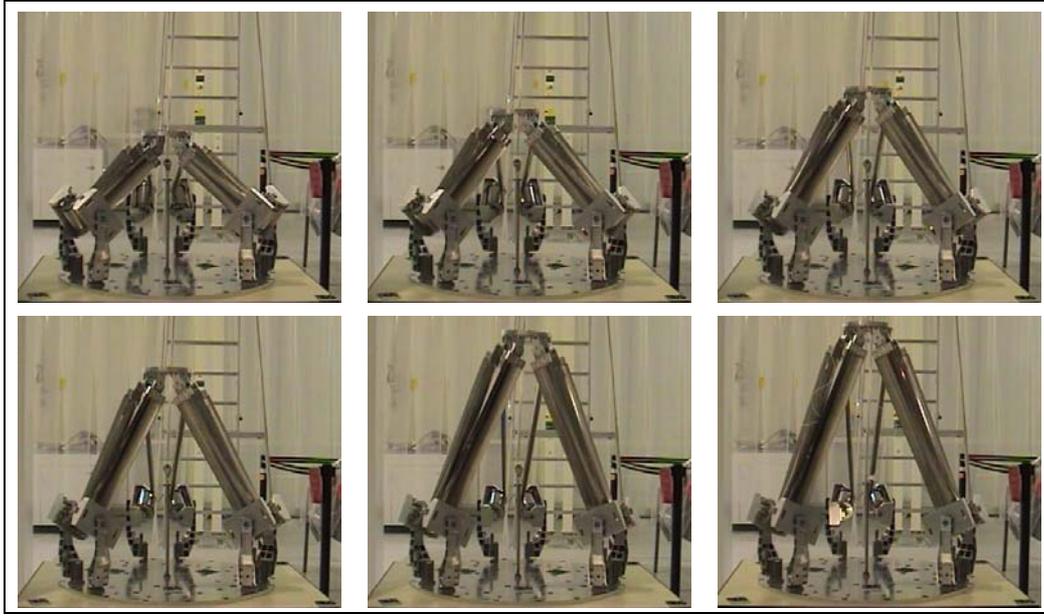
The active wrist concept used for this hexapod implies the use of one spherical joint at the top and one universal joint at the base of each leg which means that 2 DOF are required at the base of the tape-spring and 3 DOF at its top. For the base junction, the coiling of the tape-spring has been used as a degree of freedom in rotation. The second degree of freedom, required for control and deployment, is given by an axis mounted on angular contact ball-bearings holding the cradle of the coiling mechanism. The top junction is made by an axis mounted on two angular contact ball bearings, by a thin metallic blade whose flexure brings one DOF in rotation and by the torsion of the tape-spring itself.

The hexapod is constituted with a base-plate on which 6 linear stages are mounted on  $90^\circ$  brackets. The linear stages support the bottom junctions and allow vertical displacements of the coiling mechanisms on a 16 mm stroke with a  $20 \mu\text{m}$  precision.

The intersection of the rotational axes and the hinge axes at the top and base junction have been precisely placed at the positions calculated with optimal design.

## 5 - DEPLOYMENT TESTS

The deployment tests aimed at characterising the deployment reproducibility of the hexapod in 2 configurations: the flexural configuration which is the nominal configuration and the rigid configuration in which the flexible blades have been replaced by thick rigid blades. This way the top junction has only 2 DOF instead of the 3 required for control. This allows a better stability of the platform during deployment but reduces severely the correction range of the hexapod.



**Figure 3 : Rigid configuration deployment**

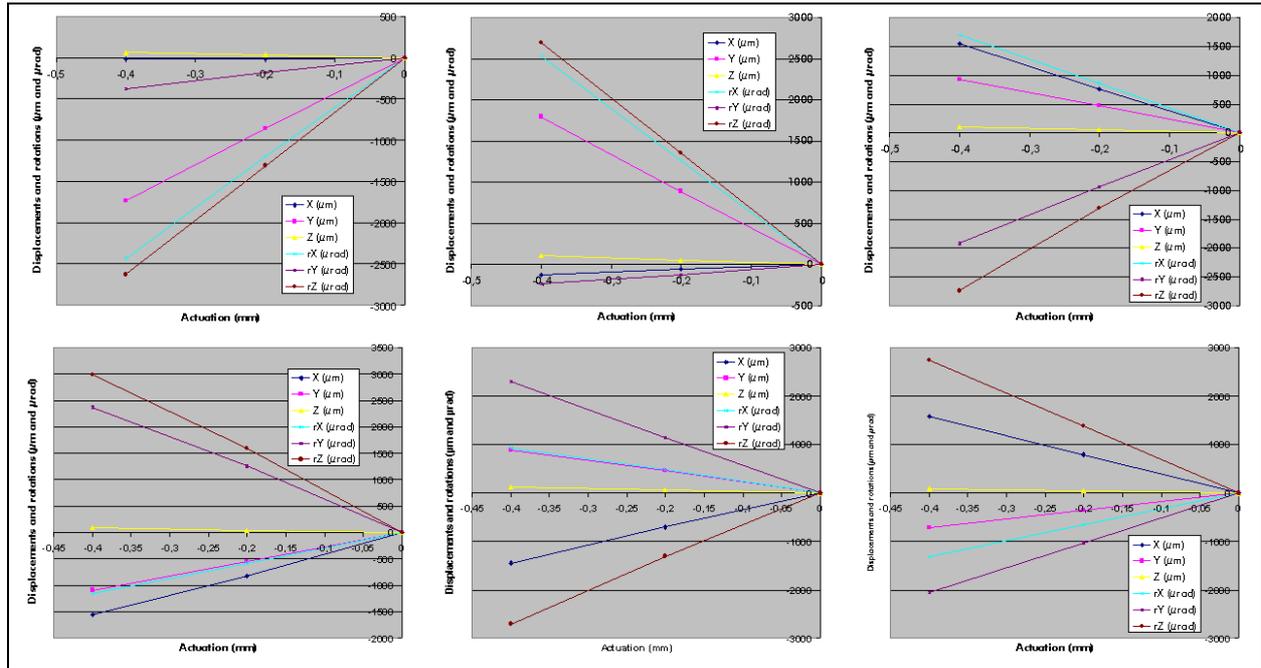
The tests consist in releasing the locking of the platform on its stowing point to let it reach the deployed position. Then, the final position of the platform with regard to the base-plate is measured thanks to videogrammetry which allows a  $10\ \mu\text{m}$  measuring precision without contact.

For the flexible configuration, the first tests showed that the self-deployment requires a regulation of the 6 tape-spring uncoiling. Then, we decided to help manually the platform to stay horizontal on its path and to «drop» it once the deployed position reached. In the rigid configuration, the platform stays horizontal during deployment and only needs a speed regulation to avoid the end-of-travel shock. This has been achieved with a single-wire regulation system controlling its speed.

In rigid configuration, the 23 deployments performed showed maximal translation and rotational deployment errors of  $240\ \mu\text{m}$  and  $700\ \mu\text{rad}$ . In flexural configuration, the 12 deployments performed showed maximal translation and rotational deployment errors of  $940\ \mu\text{m}$  and  $2000\ \mu\text{rad}$ . These deployment errors are widely included in the workspace guaranteed by optimal design and should be corrected by the hexapod.

## 6 - CORRECTION TESTS

Two levels of actuation have been applied to each of the 6 feet to identify a linear behaviour model of the hexapod. The displacements of the platform generated by feet actuations are presented on the figures hereafter.



**Figure 4 : flexural configuration platform displacements under feet actuation**

These tests showed that in the workspace of the hexapod, the behaviour is linear. Then, the jacobian matrix of the hexapod has been identified through the slopes of figures above. With the inverse of this jacobian matrix, a theoretical set of actuation has been calculated to perform a 1 mm translation along  $X$  axis. Each component of this theoretical set has been rounded to the precision of the actuators and applied to the breadboard. The theoretical and experimental displacement are presented hereafter.

	$dX$ (mm)	$dY$ (mm)	$dZ$ (mm)	$d\theta X$ (mrad)	$d\theta Y$ (mrad)	$d\theta Z$ (mrad)
<b>Tests</b>	-0.946	-0.029	0.009	-0.047	0.590	-0.051
<b>Theoretical</b>	-0,918	-0.039	-0.020	-0.074	0.544	-0.089

**Table 1 : correction test**

On the two principal components of the displacement ( $dX$  and  $d\theta Y$ ), the difference between theory and test is 3% and 8%. On  $dY$  and  $dZ$ , the displacement errors have the same size as the measuring error. On the other components, the displacements are small and the differences are about 3 times the measuring precision. This test shows that a correction displacement could be imposed to the platform with a satisfying precision considering the measuring errors and the actuators precision.

## 7 - CONCLUSION

This study has allowed us to develop a breadboard of an hexapod which can be deployed thanks to 6 tape-springs mechanisms and whose pose can be corrected with 6 actuators.

The deployment errors are included in the workspace of the hexapod and can be corrected as the hexapod exhibits a linear behaviour in this domain. A full calibration campaign of the breadboard with the use of finer actuators should lead to a better precision of the correction of the platform position.

This study shows that tape-springs can be used to design deployable hexapod with satisfying deployment reproducibility and correction capabilities.

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