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"STURDY AS A HOUSE WITH FOUR WINDOWS",

THE STAR TRACKER OF THE FUTURE

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Abstract

Ongoing miniaturization of spacecraft demands the reduction in size of Attitude and Orbit Control Systems (AOCS). Therefore TNO has created a new design of a multi aperture, high performance, and miniaturized star tracker. The innovative design incorporates the latest developments in camera technology, attitude calculation and mechanical design into a system with 5 arc seconds accuracy, making the system usable for many applications. In this paper the results are presented of the system design and analysis, as well as the performance predictions for the Multi Aperture Baffled Star Tracker (MABS). The highly integrated system consists of multiple apertures without the need for external baffles, resulting in major advantages in mass, volume, alignment with the spacecraft and relative aperture stability. In the analysis part of this paper, the thermal and mechanical stability are discussed. In the final part the simulation results will be described that have lead to the predicted accuracy of the star tracker system and a peek into the future of attitude sensors is given.

Keywords:
Optical design, Mechanical design, Analysis, Star tracker, Attitude control, Monolithic design, Integrated attitude control sensors.

1 Introduction

Traditionally, star tracker systems consist of a housing that fixates an optical system, big cone shaped baffles (Figure 1) and a bracket to hold multiple star tracker units. To ensure optimal performance, the system is then accommodated on the outer surface of the satellite facing away from the earth and the sun. Alternatively star trackers are largely lowered into the satellite structure to avoid parts that protrude the available mechanical envelope. Because spacecrafts are decreasing in size, the star trackers should also be miniaturized in order to avoid that the star tracker becomes the largest system part. The main obstacle in the miniaturization process is the fact that the baffle, used to avoid sun illumination of the aperture, cannot be deleted from the original design. Although it taking up a large portion of the star tracker system the size of the baffle can not be reduced, as baffle size will strongly influence the performance of the system. In a normal star tracker design, reducing the size of the baffle will eventually render the star tracker useless. New designs of miniaturized star trackers are already in use, bringing with it the benefit of a lower mass and smaller size. The drawback with these designs is nevertheless the mass and the size of the baffle that remains. For a system that uses multiple optical heads, the units also will have to be assembled separately on a stable structure or bracket, adding additional mass and assembly costs for the overall system. For the miniaturization of star trackers to make the next step, a drastic change in sun blinding prevention has to be made.

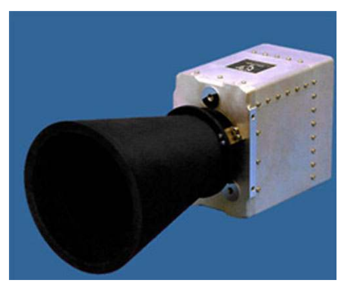

Figure 1 A star tracker module

The MABS is developed as a star tracker system without baffles, in which several apertures are mounted together in a single mechanical structure, and sun illumination of one or even two apertures can be accepted without significant loss of performance.

When determining the attitude of a spacecraft three axes have to be determined. A star tracker is used in case high accuracy is required and many satellites employ two or three star tracker units. The use of two (or more) star trackers under an angle will allow a drastic improvement of the roll performance and will prevent the loss of attitude if one aperture is blinded by the sun. Because of the lager number of apertures in the MABS concept, some can be blinded without suffering a large decrease in accuracy. In the MABS design the apertures are situated in such a way that the attitude can always be determined without the use of baffles.

2 Requirements and constraints

2.1 Major requirements

For MABS the following requirements where formulated:

- An attitude determination accuracy of <5 arcsec.
- Minimum size
- Weight goal of < 1kg
- Able to cope with direct sun illumination without getting outside of specifications.
- Sufficiently rigid to survive the vibrations caused by the launch of a spacecraft.
- "Low cost off the shelf product" due to design for manufacturing and minimum component count.

2.2 Design constraints

Being the backbone of the star tracker, the opto mechanical subsystem (housing and optical elements), is of the utmost importance. To ensure proper operation in space after launch, it must be thermally stable and able to withstand the severe vibrations during the launch period. By insulating the main structure and making it as light and compact as possible, a suitable platform can be created to house multiple optical units. The following table specifies the main requirements for the housing.

Requirement	Required value
Thermal range	-40 to +60 ºC
Natural frequency	>200 Hz
Mass (target)	1 kg
Dimensions (target)	120 x 120 x 80 mm

3 The design

3.1 Multiple aperture principle

Regarding the main criteria for star tracker design, we can identify three main elements critical to the star tracker system:

- Stability of the mechanical system
- Type of optical system
- Size and type of baffle used

As previously mentioned, one of the main obstacles in designing optical space instrumentation is preventing direct illumination of the detector. Until now this is always solved with the use of baffles and/or mechanisms, shielding the aperture from the sunlight. These baffles add a lot of mass and size. With a larger number of apertures less shielding is required. In the MABS design a layout with four apertures is used, that are placed in an orthogonal pattern as depicted in figure 2. The structure containing the optical system acts as a sun baffle, blocking out the sun for the opposing aperture, as depicted in figure 3. In the design each aperture has its own optical unit and detector, thus avoiding straylight propagation internal to the structure. In this situation the aperture on the right is blinded and the aperture on the left is shaded and thus still working. In case the sun swaps from side by rotation of the spacecraft. The blinding and shading is also swapped, thus always leaving one aperture working. This has lead to the conclusion that with the use of multiple apertures, the large cone shaped baffles can be eliminated, reducing the overall size drastically.

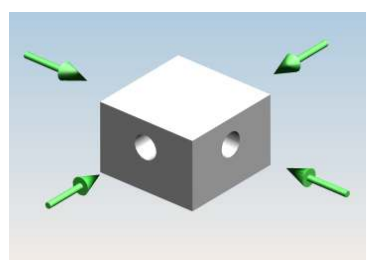

Figure 2 Multi-aperture layout. Four apertures are placed in a orthogonal pattern.

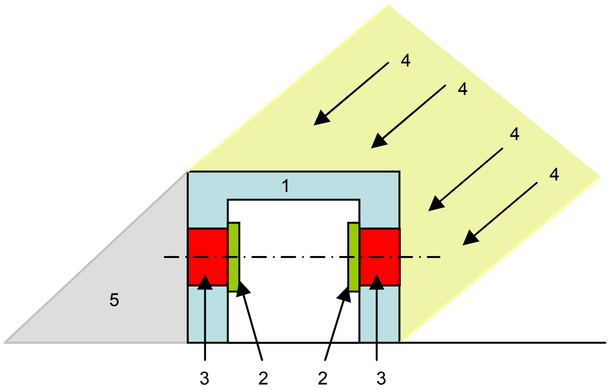

Figure 3 Schematic presentation of sun blocking. The numbers in the figure 3 represent: 1 Housing, 2 Detector, 3 Aperture, 4 Sunlight and 5 Shade.

3.2 Optical design decisions

The largest tradeoff made in this respect is whether to use reflective- or refractive optics. In case of the MABS, reflective optics is chosen above refractive optics because of the following advantages:

- High efficiency because of less optical elements
- No chromatic aberrations
- All aluminium solution
- Possibility of direct assembly
- Ability to produce elliptical apertures with a simple optical system

In the presented concept, the star light is reflected and focused onto the APS-sensor by means of two mirrors. The design is such that the optical axis is pointing 30 degrees off zenith, thus leading to 60 degrees between two startracker apertures. The use of one conical and one knife shaped baffle directly integrated into the structure allows reducing the sensitivity of the detector to straylight that could otherwise be entering the optical system. In the mean time they also assist in maintaining a high eigenfrequency.

3.3 Mechanical design

With a monolithic structure as backbone, is feasible to position the optical units in reference to each other, based on manufacturing tolerances only. This saves on fabrication and assembly costs and positively contributes to the low cost aspects of the design. An exploded view is illustrated in figure 4. The exploded view shows how the mirrors and the detector are situated with respect to the housing. The electronics compartment is situated on the bottom of the housing and the structure is covered with MLI for thermal insulation and reduction of heat input in case of direct sun illumination. With the electronic compartment situated on bottom of the structure, the distance of the electronics to the spacecraft is as short as possible, providing interface advantages.

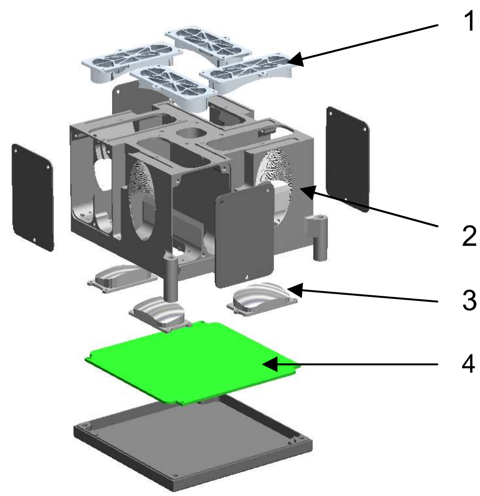

Figure 4 Exploded view of MABS. The number in figure 4 represent: 1Upper mirror, 2 Monolithic housing, 3 lower mirror, 4 Electronics

In the process of mounting the optical components, kinematic mounting is used. This results in low induced stresses on the optical components when mounted, or when ambient temperature changes. The kinematic mount is performed by the kinematic design method used by Koster [1].

4 Analysis and performance prediction

The main mechanical design feature that makes MABS unique is the monolithic housing. As mentioned above this has firstly a major advantage above state of the art sensors in alignment of the units with the spacecraft during integration and secondly in being stiff and thermally stable during respectively launch and orbit phases. In the following chapters the findings on modal analysis, random vibration analysis and thermal simulations are elaborated upon. The performance is predicted with the use of the SSATT Tool.

4.1 Modal analysis

The first mode (torsion) of the monolithic housing is in the range of 1300 Hz frequency as depicted in figure 5, resulting in low stresses during launch and the ability to survive even the most demanding launch environments. The result of the mechanical design and vibration simulation show that the current design rendered a stiff and light monolithic structure. The four optical units have to be separated mechanically to avoid blinding by means of straylight internal to the structure, in case of direct sun illumination. This mechanical separation of the optical systems is performed by placing the optical systems in separate boxes.
The low mass and high stiffness are a result of the use of thin-walled design and smart use of 'jointly-used' structures. The electronics compartment is located in the bottom of the structure, thus lowering the centre of gravity as far as possible. These design features give MABS the necessary properties to perform as a high precision instrument and survive the harsh launch environment.

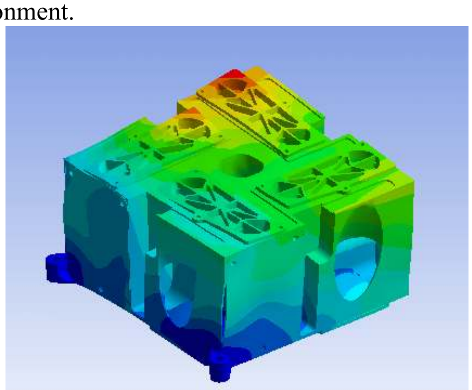

Figure 5 First mode of Natural frequency. This picture shows a torsion movement around one of the mounting points.

4.2 Random vibration analysis

Taking the requirement 'off the shelf product' in mind, a high value for the power spectral density (PSD) was chosen to demonstrate the capability to survive very severe launch environments. The vibration simulations are performed with a PSD of:

20 - 100Hz	+3db/oct
100 - 400Hz	1,4g2/Hz
400 - 2000Hz	-3db/oct

The result of the random vibration analysis is a margin of safety of 1.3 which indicates that the star tracker system is rigid enough to survive just about any launch load and hence structural specifications will be driven by sensor and electronics specifications..

4.3 Thermal stability

The thermal stability of the design is investigated by simulating the heat of the sun on one surface of the star tracker. The angle of inclination used in the simulation is 45 degrees illuminating two apertures at once, while the star tracker is mounted on a thermal stable spacecraft. The rotational deformation (calculated with equation 1) caused by heating of the surface is well within the tolerance analysis resulting from the optical design. A schematic of the deformation is depicted in figure 6 and 7.

$$\alpha = \arctan \frac{x_2 - x_1}{l} \qquad (1)$$

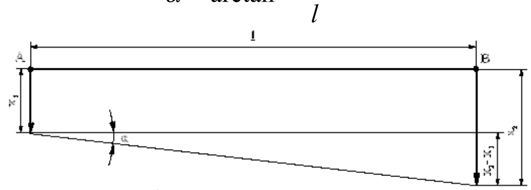

Figure 6 Schematic of deformation

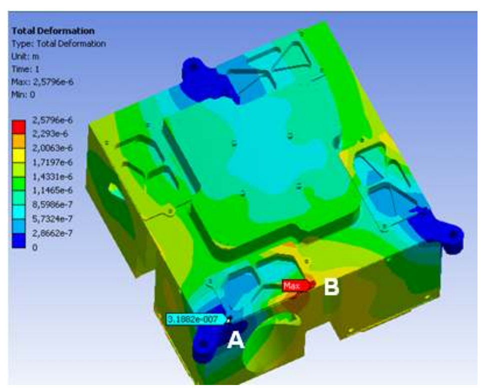

Figure 7 Thermal simulation

4.4 Performance prediction

The MABS preliminary performance is estimated with the help of an upgraded version of the Star Sensor Algorithm Test Tool (SSATT [2]) tool. SSATT is a tool for:

- Supporting star sensor camera hardware development
- Supporting star sensor algorithm development
- Assessment of performance of existing sensors.

The SSATT features are:

- Star Catalogue conversion from visual to instrumental
- 4 Triangle Based recognition algorithms, validation algorithm and Quest attitude estimator
- Optical binary processing
- Database organization and uniformization for pointer based triangle finding
- Automated on-board database production
- Simulated customized camera images
- Monte Carlo simulations over the full sky
- Input and batch processing of real or centroïded images
- Genetic algorithm optimization of hardware imperfections
- Multiple camera operations [upgrade for MABS]

The SSATT Tool was successfully employed to evaluate the performance of the MEFIST [3] hardware based on real sky images. For MABS a first model of a potential MABS configuration (LCMS [4] sensor which has 512x512 pixels, focal length 29.3mm, 4 cameras) was implemented to provide a first indication of estimated performance. The preliminary results indicate that the required performance of 5 arcsec accuracy can be met. Moreover the results reveal that the reconstructed rotation of the camera is in the same order as the longitude and latitude reconstruction. With conventional cameras the rotational reconstruction accuracy is an order of magnitude larger.

The increased longitude/latitude accuracy is due to the increased number of stars that are recognized by having four rather than one camera. The longitude/latitude accuracy is proportional to one over the square root of the number of stars.
Hence with four cameras the accuracy is on average a factor two better than of a single camera in longitude/latitude direction. The rotation reconstruction which is dictated by the distance of the stars in a Field Of View increases as of the offset in the camera directions, which can be interpreted as one large virtual Field of View for rotational reconstruction.

Ongoing work is firstly to model in more detail the LCMS sensor and therewith generate synthetic images. The algorithms will be optimized for the specific hardware settings and batch processing of the synthetic images will allow for full statistical analysis.

5 Ongoing development

Based on the MABS patent, TNO is currently designing a new generation of high precision attitude control sensors, in which multiple apertures are integrated in a monolithic structure. Additionally also sunsensors will be integrated in the same structure and possibly even a (number of) GPS receivers. A design will be presented that reaches accuracy of 5” and with a target of 120 x 120 x 100 mm as an overall dimension. The final goal of the project is to construct a new attitude (and orbit) control sensor which is universally applicable and because of the simplicity in the design and fabrication methods, will be an “off the shelf product”, ready to be used on many spacecraft.

At this moment in time a consortium of Dutch companies consisting of Delta Utec, Cosine, Systematic design Bradford Engineering, ISIS and TNO is working on this new integrated sensor dubbed IOPACS (Integrated Optical Attitude Control Sensor)
IOPACS (depicted in figure 7) will be using a sun sensor array (1), a multi aperture high precision star tracker (2) and four GPS systems (3) to determine the attitude and position in space. With the development of IOPACS, an integrated solution is provided that will enhance attitude and orbit determination to micro and nano satellites.

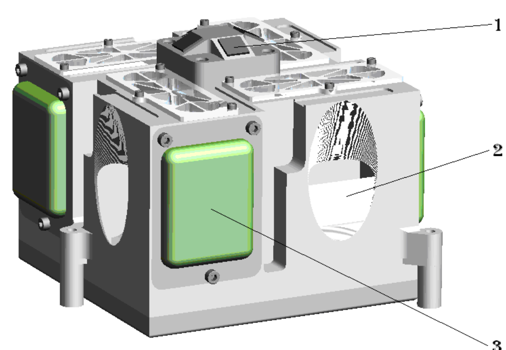

Figure 8 IOPACS (TNO)

6 Conclusion

The tendency of miniaturization spacecraft is set and if the star tracker isn't allowed to become the driving factor in spacecraft size it must also be miniaturized. When taking the presented new approach on aperture use and housing structure in mind, new designs are possible with many benefits in the area of size, performance and fabrication costs. Although a working prototype is yet to be build, the multi-aperture design shows a lot of potential and further research on the approach will lead to further miniaturization and the fabrication of miniaturized attitude sensors

Within this paper TNO and its partners have indicated the possibilities of the Multi aperture star tracker design. The use of a monolithic housing combined with a reflective optical system will result in a stiff, low mass, low volume structure. Design for manufacturing and a high level of integration will lead to a cost effective system. Multiple apertures and a well chosen redundancy concept will lead to a design that potentially meets all predetermined requirements as well as the ESA standards for high reliability satellites.
Looking to the near future the consortium will focus on the demonstration of the MABS capabilities as a vital part for the IOPACS system. After a demonstration of the star tracking capabilities, other sensors can be added to provide the first integrated attitude (and orbit) control sensor which is intended to become a plug and play component for many satellites to come.

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