TEST AND PERFORMANCE ANALYSIS OF THE NEW STAR TRACKER STELLA

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Abstract

STELLA is a miniature star tracker for pico and nano satellites developed at the University of Würzburg under financial support of DLR (FKZ 50RM0901). The star tracker features small dimensions and weight as well as low power consumption and fulfills therewith major boundary conditions and requirements of small satellite missions. This paper discusses the verification process of the STELLA star tracker. This process includes functional, performance and environmental tests. Functional tests have been done using a star simulator and were confirmed during field experiments. Furthermore influences of disturbances such as false stars (space debris, satellites, comets) were explored. The paper also presents an evaluation of some advanced functionalities: pixel failure detection and recognition of interference from the Sun, the Earth and the Moon. Subsequently to functional tests investigation of accuracy performance was done. The star tracker has been subjected to a full qualification program, which includes thermal-vacuum, shock, vibrations and radiation tests. The paper explains results of the tests and star tracker performance and shows, how successful the design requirements are met. The lessons learned contribute to advancement of the next generation of miniature star trackers.

1. INTRODUCTION

A star tracker is a key component of attitude control systems for very precise attitude determination. The basic idea behind the functionality of star trackers is usage of the steady position of stars on the celestial sphere as a reference system. An autonomous star tracker takes pictures of the star sky and compares these images with an on-board star catalog. As soon as a star pattern is recognized, the sensor can compute an orientation of the spacecraft.

This very robust and accurate technology has been used in big satellites for a long time. Unfortunately the average star trackers available on the market are too large and too heavy to be integrated into small pico or nano satellites.

2. STELLA SENSOR OVERVIEW

The STELLA star sensor was developed especially for pico and nano satellites [1]. Performances, functionality, as well as energy and space needs are tailored to requirements and constrains of these satellite classes. The star sensor is very compact and light. Without baffle it weighs only 120g and consumes about 200mW. More detailed specification is presented in table 1.

Furthermore, STELLA has some particular features, which usually distinguish only the big star trackers weighing several kilos:

– Entire software can be reloaded for all embedded processors (FPGA, DSP, µC).
– Lookup table and star catalogue can be updated via telecommand (TC), in order to restore the system in case of bit flipping through radiation effects.
– For optimal adaption of the star tracker to the space environment in different orbits and for various missions, it is possible to parameterize relevant parameters of the image sensor and attitude determination algorithm by TC.
– The star tracker can detect interference from stray light of the sun, the earth and the moon.
– For validation purposes users have the possibility to download raw images and the corresponding algorithm parameters.
– Almost all critical components in the power and communication system are redundant.
– The sensor features a modular structure, so that sensor head and electronics can be installed separately from each other.

Parameter	Value
Accuracy (estimated)	0.01° pitch/yaw, 0.04° roll 3σ
Field of View	14,3°diagonal
Power Supply	3,3V
Power consumption (average)	200mW
Dimensions excl. Baffle	60 x 46 x 58mm^3
Mess excl. Baffle	120g
Operation Temperature	-25°…+55°C
Life time in LEO	2 years (ref. orbit 500km)
Data output	Quaternion
Output data rate	4Hz
Main interface	2xCAN 2.0B, 2xUART

Table 1. Specifications STELLA star tracker

Figure 1. The STELLA Star Tracker

A star tracker is a multi-component system, consisting of optical and electronic systems, software and a mechanical structure. All these system components are interdependent. Modification or variation of one of the components will cause changes in the whole system and influence values and accuracy of sensor output. This requires iterative and careful tuning of all system components.

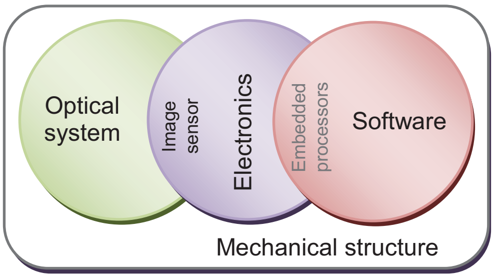

Figure 2. Basic structure of star tracker

The major components of STELLA will be discussed in the next subsections.

2.1. Lens and mechanical design

Specifically for STELLA a low light lens with focal length of 25mm and aperture F1,6 was designed. In combination with an 1/3-inch image sensor the optical system provides a field of view of about 11,5° x 8,6°.
The main task of during lens design was to keep the system small, light and free from optical aberrations. First of all the lens should be distortion “free” to avoid adverse influences on the measurement of stars position. A slight pincushion distortion of less than 0,1% and lateral color aberration of less than 1,2µm were obtained.
The whole opto-electronical system allows detection of stars of magnitude up to 7 at an exposure time of 100ms. This ensures theoretical sky coverage of 98.8% with more as 3 stars in field of view and creates optimal condition for all common star identification algorithms [2].
Suitable to the sophisticated lens the mechanical structure offers high stability and strength. The camera housing consists of four solid aluminium frames arranged in a stack.

2.2. Electronics of the star sensor

The major component of the STELLA star camera is a low light and low power CMOS imager. The sensor has a resolution of 840 x 640 pixels and can take up to 60 frames per second. The image date is outputted in parallel with a depth of 8 Bit.
The control and data handling system of the image sensor comprises FPGA and shared SRAM. These components are placed on the Image Sensor Board (ISB) with a dimension of 40 x 40 mm.
In order to detect stars and compute attitude an image recorded by ISB will be processed on a DSP 5000 from Texas Instruments. The star catalogue and the look up table used in the employed algorithms are stored in 8M flash memory located on the Image Processing Board. The calculated attitude will be output as four quaternions.
The last of three boards is the Service Board containing two redundant microcontrollers, which establish communication to the board computer via CAN2.0B and manage all the TM and TC. Other functions are control of the power unit and collection of the housekeeping data.
All electronic components are industrial versions of commercial of the shelf components and are ITAR free.
The mentioned three electronic boards are fixed in aluminium frames of the stack structure.

2.3. Software

Software for attitude determination can be subdivided into three main parts: recognition of bright objects and stars, identification of stars, attitude calculation.
Objects brighter than a user defined threshold value will be recognized by region labeling of the image. This method allows detection of not only stars but also disturbances from stray light of the sun, the earth or the moon.
The next step of the entire algorithm is star identification. The stars detected in image will be matched with stars in the catalog by the extended Polestar (Circle pattern) method [3]. The Polestar method is a pattern recognition method based on a tournament approach and thereby is robust against false star recognition. Another specialty of the Polestar method is that the lookup table has no geometrical parameters of star constellations but uses unique pattern vectors similar to bar codes.
The identified image stars and associated catalog stars establish a basis for a computation of attitude via the TRIAD or the QUEST method.

3. TEST PROGRAM

The STELLA star sensor has been subjected to a very wide test and qualification campaign:

- Functional and performance tests:
  - Night sky tests for algorithm validation
  - False star test
  - Determination of the star tracker’s accuracy
  - Tests in motion
  - Stray light test
- Qualification tests:
  - Vibration and shock tests
  - Radiation test
  - Thermal vacuum test

3.1. Functional and performance tests

To verify functionality and performance of STELLA several tests have been performed. There were two main goals for these tests. First, the system design had to be evaluated and approved. Next, hardware and software reliability and long term stability tests under close to reality conditions were carried out.

3.1.1. Validation of attitude determination algorithm

A number of night sky tests were performed to evaluate the attitude determination algorithm. They have been carried out in January 2011 near Würzburg. During these tests the star camera was oriented towards random constellations close to the zenith. This emulated a Lost in Space situation. For exact orientation of the sensor an electrically driven telescope mount with a finderscope was used.
The captured images with their associated quaternions and mount orientations were collected and analyzed. For each set of quaternions a star sky was simulated and compared with downloaded from the camera image. Although surroundings of Würzburg are not an optimal place for astronomical observations and some stars were missing in the image, 98% of attempts were successful and the constellation was recognized. In most of the failed attempts one or more interferences (aircrafts) were observed. The average durations of Lost in Space solutions amounts to 600ms.
An example image with its set of related quaternions is presented in figure 3. The image shows a part of the Cassiopeia constellation. A simulated image based on quaternion information is visualized in figure 4.

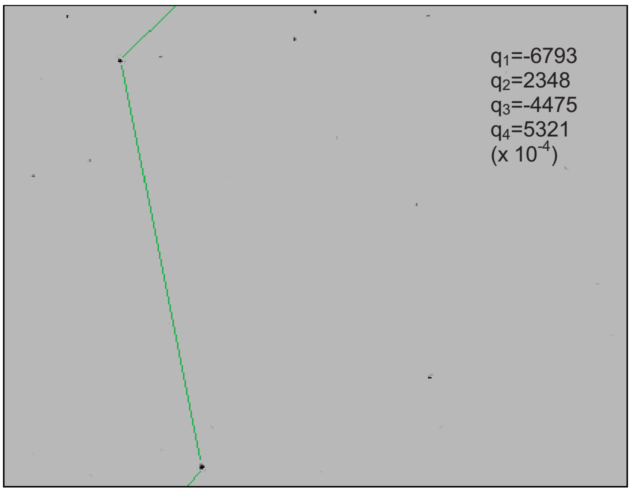

Figure 3. Night sky image

Similar tests were performed on a self-developed star simulator. For that a section of star sky is pictured on a LCD screen. One of the disadvantages of the LCD Simulator is its non parallel spread of light rays. To account for this, the camera lens should be refocused or collimator optics has to be used. Furthermore, the LCD screen was on its contrast limit, because of background light. According to this the exposure time has to be reduced.

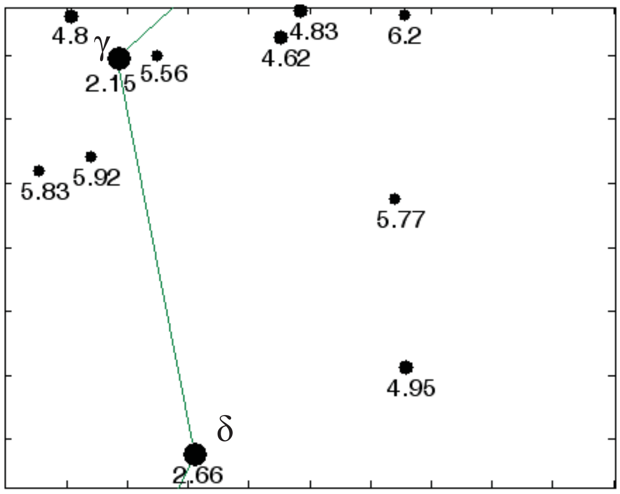

Figure 4. Simulated image

3.1.2. False star test

For star trackers which are operated on satellites in LEO the problem of false stars caused by space debris, satellites or asteroids is significant and can lead to incorrect attitude estimation. In order to verify the robustness of STELLA's algorithm against disturbances a number of false star tests were executed. Up to 25 false stars were inserted in recorded images. The result of 1000 random simulations for the image shown above is presented in figure 5.

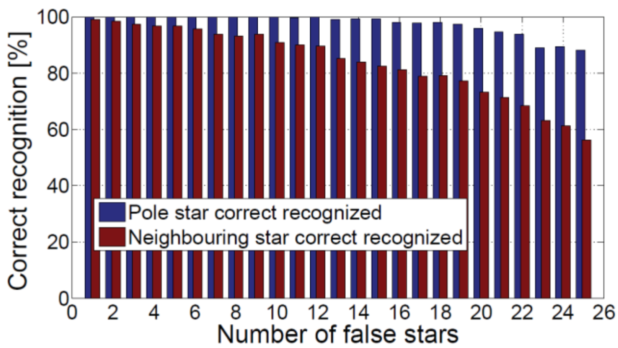

Figure 5. False star analysis

The analysis shows that the pole star will be correctly recognized even if 12 false stars are pasted into the image. This can be explained by the fact, that in contrast to triangle or polygon algorithms [4, 5] the circle pattern method [1, 3] used in STELLA is a tournament approach to find the best suitable star candidate.
For neighbouring stars the probability to be correctly recognized is lower as for a pole star and amounts to 98% already at 2 false stars in the image. In this case the circle pattern method shows the same behavior as other algorithms.

3.1.3. Determination of star tracker accuracy

The estimation of the star tracker accuracy was done under real sky conditions. The star tracker was pointed close to the zenith and put in attitude determination mode at reduced output rate of 1Hz. Several trials were performed on different days. The figure shows one of the continuous measurements of attitude determined by STELLA. The outputted quaternions have been converted in declination, right ascension and roll. As expected, the right ascension changes linearly accordingly to the Earth rotation, the declination and roll remain constant. For declination and roll the achieved accuracies are 0,01° and 0,04°±3σ. These values correspond to the design values.

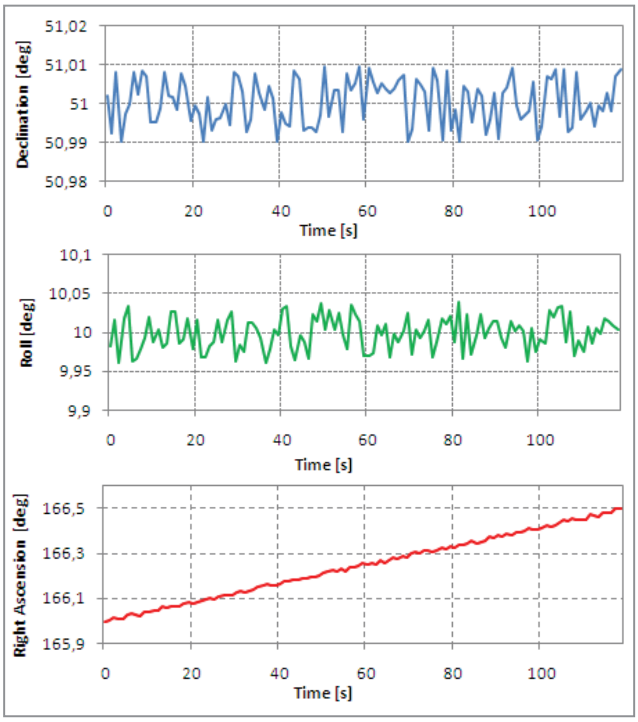

Figure 6. Star tracker output

3.1.4. Test in motion

In order to test the behavior of the attitude determination algorithm while camera is moving some experiments on the night sky ware done. For these experiments the camera was rotated with variable velocity around different axes by the telescope mount mentioned above.
The tracking sequences evidence, that optimal accuracy can be achieved at angular velocity of less than 0.3°/s. Up to 0.5°/s the star tracker works with reduced accuracy, while the number of false identifications increases at the same time. At rotation rate of more than 1°/s no identification is possible because of grave smearing of the stars in the image.

3.1.5. Stray light test

A stray light test was performed to prove a design sun exclusion angle of the baffle, which amounts to 40°. The measurement was done by using the sun simulator in combination with the star simulator. The sun simulator was mounted on a mobile platform on level with the x-axis of the star camera. The camera was permanently observing the star sky on the screen of the star simulator. The angle of sun light rays was decreased from 90° until the star sensor broke off identification and detected a large object. The measurement results meet the design specifications.

3.2. Qualification tests

Qualification tests have been arranged according to ECSS-ST-10-03 standard [6] and include mechanical tests and thermal vacuum test as well as a subsequent radiation test.

3.2.1. Mechanical tests

The mechanical test program contains sine vibration, random vibration and shock tests and should simulate stress from launch vehicles.

Vibration tests

Vibration test have been carried out for all three axes under conditions specified in tables 2 and 3. For each axis a resonance search between 5 and 2000Hz by 0.5g and a sweep rate of 2 oct/min has been performed. In the mentioned frequency range no resonance effects were detected.

Frequency	Level
(5 to 21) Hz	11mm
(21 to 60) Hz	20g
(60 to 100) Hz	6g
Sweep rate: 2 Oct / min	

Table 2. Sine vibration levels

Axis	Frequency	Level
Vertical: z-axis	(20 to 100) Hz	+3dB/Octave
	(100 to 300) Hz	$2.0g^2/Hz$
	(300 to 2000) Hz	-5dB/Octave
	Overall	34.41 g_{RMS}
Lateral: x, y - axes	(20 to 100) Hz	+3dB/Octave
	(100 to 300) Hz	$0.86g^2/Hz$
	(300 to 2000) Hz	-5dB/Octave
	Overall	22.21 g_{RMS}
Duration: 2,5 min per axis		

Table 3. Random vibration levels

Before and after each vibration sequence functionality and integrity of the star sensor were tested. The test includes the following steps: functional check of the attitude determination algorithm, image download, temperature and power consumption monitoring and focus control.

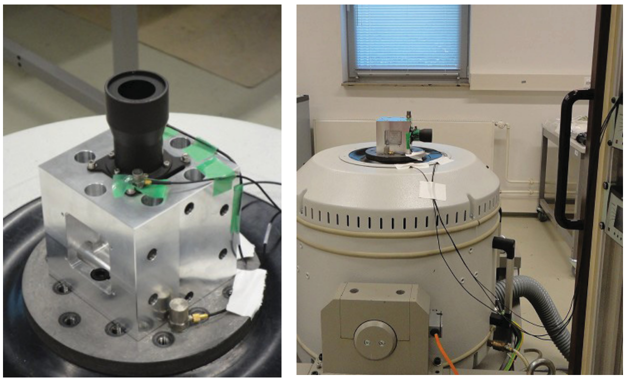

Figure 7. Vibration test of STELLA

Shock tests

Three tests for each axis under settings listed in table 4 and shown in figure 8 have been executed.

Frequency	Level
100Hz	20g
2000Hz	2000g
10000Hz	2000g

Table 4. Shock level

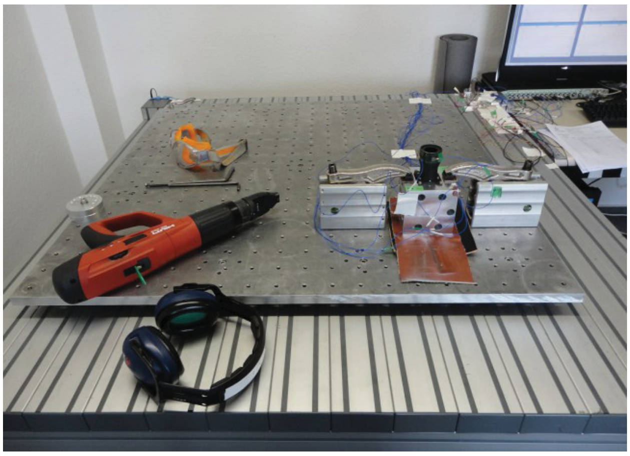

Figure 8. Shock test setup

All mechanical tests were successfully complete without any changes and damages in the EQM.

3.2.2. Radiation test

Furthermore, the STELLA star tracker has been irradiated from a Co 60 source up to a total dose of 100 Gy (10krd) to emulate the space environments [7, 8]. Over a period of irradiation time reduced functional tests similar to the ones performed during the mechanical tests were continuously carried out.

During irradiation some short ionization effects were observed in electronic circuits of the image sensor. These look like strong background noise of various grey values and could possibly be recognized as stars.

After completion of the test about forty single pixels feature deviant light sensitivity, but no pixel was completely damaged. This has no effect on the attitude determination.

Figure 9. STELLA during radiation tests

3.2.3. Thermal Vacuum Test

STELLA has been subjected to a combined cycling and vacuum test in the proprietary thermal vacuum chamber of the university. The first phase of the test began with thermal shocks between -50° and 90°C. After that a set of 8 thermal cycles was performed. Both phases were processing at pressure levels under 10^{-4}mBar. The dwell time at hot and cold qualification level was 2h. At the beginning and at the end of each thermal cycle full functional tests were performed. During the entire test internal temperature and current of the star camera were monitored and compared with measurements from control sensors.

The thermal vacuum test was carried out successfully and the EQM remained unchanged.

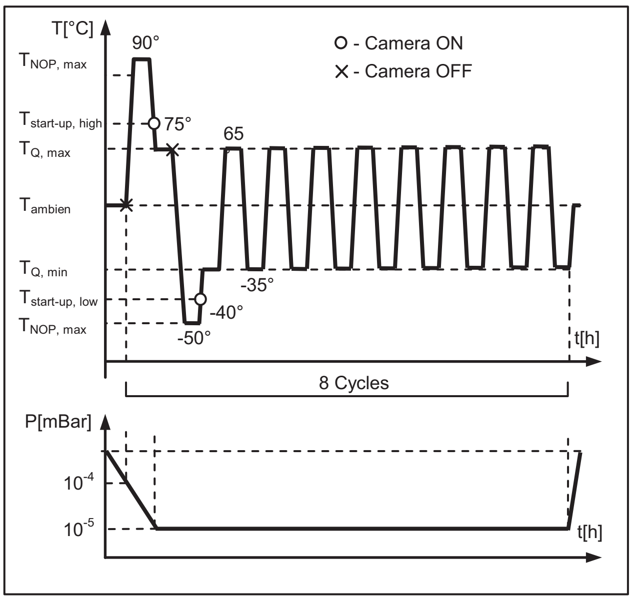

Figure 10. Thermal vacuum test sequence

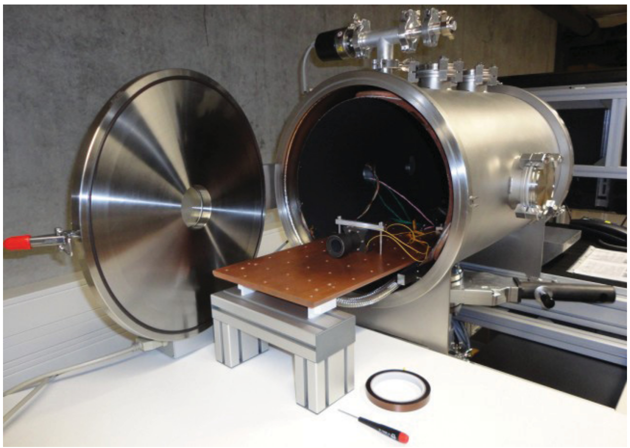

Figure 11. Set up of the thermal vacuum test

4. CONCLUSIONS

The STELLA star sensor successfully passed the full test and qualification program. Newly gained knowledge contributes to further optimization and enhancement of the star tracker system. An additional thermal-error test should be carried out, in order to estimate influences of the surrounding temperature on the accuracy of the sensor. Some steps in optimization of attitude determination should be done to achieve better behavior of the algorithms in case of ionization effects in the image sensor.

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