Star Tracker on Chip

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ABSTRACT

Nano Star Tracker on Chip (STC) is under development by Azmerit ltd. and Sternberg Astronomical Institute of Lomonosov Moscow State University (SAI MSU). This stellar sensor is designed first of all for micro and nano satellites, but can also be used on larger spacecrafts. Its dimensions, which are 73×57×23 mm (or about 30×30×50 mm in another embodiment), its weight, which is less than 65 g, and its average power consumption of 250 mW (1W peak) enable to use it in a CubeSat satellites. The STC offers a set of standard interfaces (RS485, RS232, etc.) and accepts input voltages of 3.3 V to 5 V. The features of STC are: 1) focus mainly on the Russian market of small satellites, thus it is assumed to use mostly the Russian electronic components while manufacturing, 2) STC has a high attitude accuracy, which is achieved through a more complicated image processing, allowing of taking into account the systematic errors. It is expected that the use of CMOS photo sensor with size of 128×128 pixels and with an update rate of 10 Hz gives the attitude error $\sigma_{XY}\approx 10''$. For a sensor of 768×768 pixels size error drops to $\sigma_{XY}\approx 1''$. Attitude accuracy improvement technique was developed in the SAI MSU. Azmerit ltd. is engaged in the manufacture and commercialization of STC.

INTRODUCTION

Spacecraft market forecasts in the next decade claim that the number of launches of large and medium-sized satellites will change slightly and will amount to 100–120 runs a year. At the same time the number of launches of small satellites will grow rapidly and will exceed this amount in the years 2016–2020. These predictions are not very accurate, in addition, the number of small satellites could increase drastically if any of the programs of their widespread use is adopted.

Typical sample of a modern nano-satellite is CubeSat line. This is satellites with 100×100×100mm outer size and the weight of a few kilograms.

Obviously, almost all equipment designed for large satellites cannot be used to micro- and nano-sattellites due to a larger size, weight and power consumption. For micro and nano-sattellites, special small-sized devices need to be developed.

This problem applies equally to the star trackers. In Figure 1 a classic and a miniature star sensors are shown on the background of the CubeSat satellite. As an example, ST-100 and ST-200 sensors by Berlin Space Technologies GmbH were chosen. Note that, with 10-times-less weight and 4-times-smaller dimensions, the compact star tracker ST-200 has the same attitude accuracy (30") as the original one.

Figure 1: ST-100 (large), ST-200 (nano) Star Trackers and CubeSat

At present we know the star trackers for small satellites of two manufacturers: S3S of Sinclair Interplanetary (Canada) and ST-200 of Berlin Space Technologies GmbH (Germany). This is insufficient to meet the requirements of growing market. Moreover, no one of manufacturers supply the Russian space industry with similar star trackers. So we decided to develop our own star tracker described below.

STC CHARACTERISTICS AND EMBODIMENTS

We assume to manufacture few models of STC differed in the used photosensor, the hull design, the traffic interface, the degree of functionality and availability of options.

In the basic design, front illuminated CMOS matrix of 128×128 pixels size with 20 μm pixel size is used. STC with this sensor has the parameters given in Table 1.

Table 1: Characteristics of STC with basic design

Parameter		Value
CMOS geometry		128×128 pixels
Pixel size		20×20 μm
ADC		10 bit
Update rate		10 Hz
Maximal angular velocity		2°/c
Lens focal length		10.55 mm
Entrance pupil		9 mm
Field of view (2ω)		19.5°
Spectral range		400 – 800 nm
Outer dimensions	with lens hood	73.5×57.0×57.8 mm
	w/o lens hood	73.5×57.0×23.5 mm
Hood size		∅30.0×34.3
Minimal Solar angle		30°
Acceptable Moon angle		10°
Weight (w/o hood & thermal blanking shield)		65 g
Slot temperature (w/o Peltier cooler)		-10°C … +10°C
Power (w/o Peltier cooler)	Mean	250 mW
	peak	1 W
Limiting magnitude		5.5^m
Volume of Stellar Catalog		2500 stars
Attitude accuracy	σ_{XY}	10"
	σ_Z	50"

If we want star tracker to be fully functional, then it should include a secondary power supply, or it can use a stabilized onboard power supply of the satellite. In the latter case, the star tracker will have a smaller size and weight. Typical size of the STC with external power supply is 30×30×50 mm, and its weight is about 50 g.

More significant miniaturization can be reached if image processing and attitude determination are performed by on-board systems of the satellite.

The design options are the power supply, the type of external interface and data format of the attitude (Euler angles, quaternion, etc.). They are carried out in accordance with the requirements of the satellite.

Main design option is the presence of Peltier cooler for photosensor, this enables to reduce dark current of CMOS. The disadvantage of Peltier cooler presence is significant increase of power consumption.

Another option is a shutter which enables to close the lens for carrying out flight calibrations (see below).

The second model of the star tracker, STC-2, based on the back-illuminated CMOS photosensor of 768×768 pixels size with 10 μm pixel size. This sensor has a significantly wider field of view, which cover more stars with higher limiting magnitude. As a result, STC-2 expected attitude errors are $\sigma_{XY}\approx1''$ and $\sigma_Z\approx3''$.

Increasing of exposure time with simultaneous reducing the update rate leads to higher measurements accuracy. However, the decrease of dark current, i.e. the presence of Peltier cooler, becomes important.

Depending on the required life time and absorbed radiation dose on the satellite orbit STC can be used with ordinary or radiation-resistant electronic components. The same concerns the materials applied for lens.

STC DESIGN

STC is planned to be used with CMOS photosensor of 128×128 pixels size with 20×20 μm pixel size and photosensitive area of 2.6×2.6 mm (see Figure 2).

STC is used with the five-lens objective with the focal length F=10.55 mm and the diameter of the entrance pupil of D=9 mm. Lenses are bleached in the wavelength range of 600±200 nm.

Lens can be made of ordinary or radiation-resistant glass depending on the customer requests.

It is desirable that STC is equipped with a lens hood which provides STC normal operation if the angle between the optical axis of the lens and the direction to the sun is at least 30°. Possible lens hood design is shown in Figure 3.

Case of STC consists of a base and a cover (see Figure 4). The base has three tenons with bores and developed contact surfaces. Two tenons are arranged symmetrically opposite each other, mounting holes in them are classy hole and classy groove. Line passing through them crosses the optical axis of the STC lens.

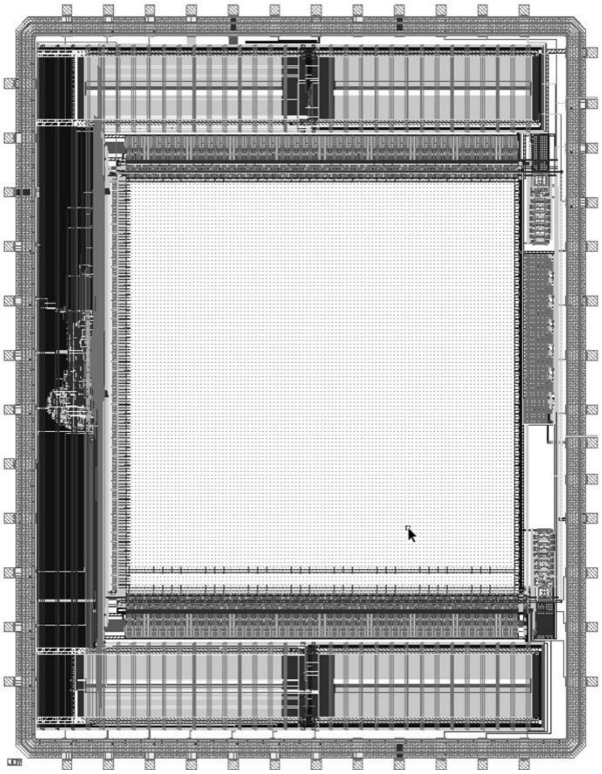

Figure 2: CMOS photosensor 128×128 pixels

The third tenon has free holes. Attaching the main board, as well as the cover to the base, is carried out by using four screws. The lens of the STC and the jack for control cable, data transfer and external power supply are set outside of the cover. The bearings shutter level and the control solenoid are set on the inside of the cover (see Figure 5).

The printed circuit board shown in Figure 5 is inside the case. On the top of the board, there are the specialized CMOS chip with a photosensor and the dynamic memory chip; flash-memory chip and microprocessor are at the bottom. There is a hole in the board under the photosensor for a possible installation of the Peltier cooler on the back side of the photosensor.

INCREASING OF ATTITUDE ACCURACY

Our numerical modeling carried out ealier[1,2] shows that minimal attitude error of a star tracker is defined by actual signal-to-noise ratio within star images. Measured signal is affected by quantum fluctuations of star light and ambient light and by sensor's noises of different nature (dark currents, readout noise, ADC error, signal conversion etc.).

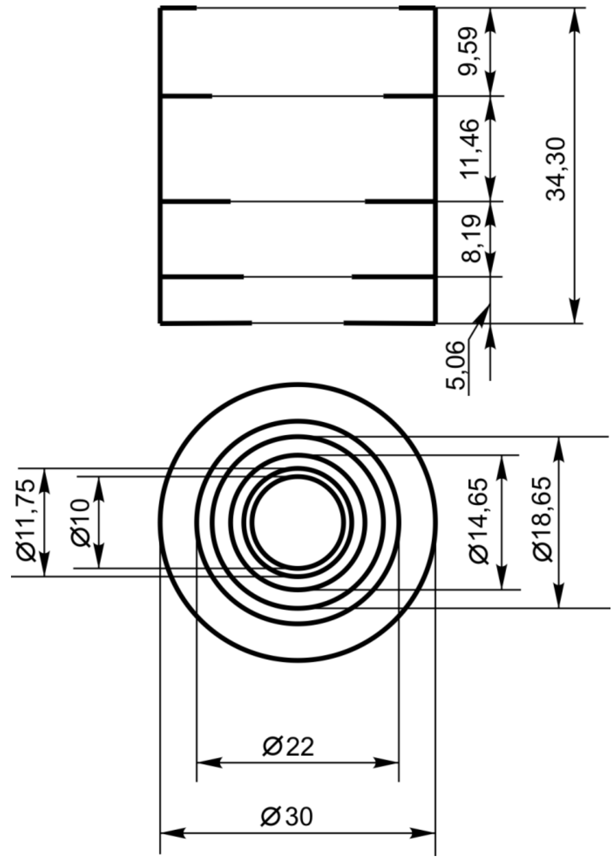

Figure 3: STC Lens Hood design. Dimensions are in mm

Figure 4: General view of STC without lens hood and thermal blanking shield

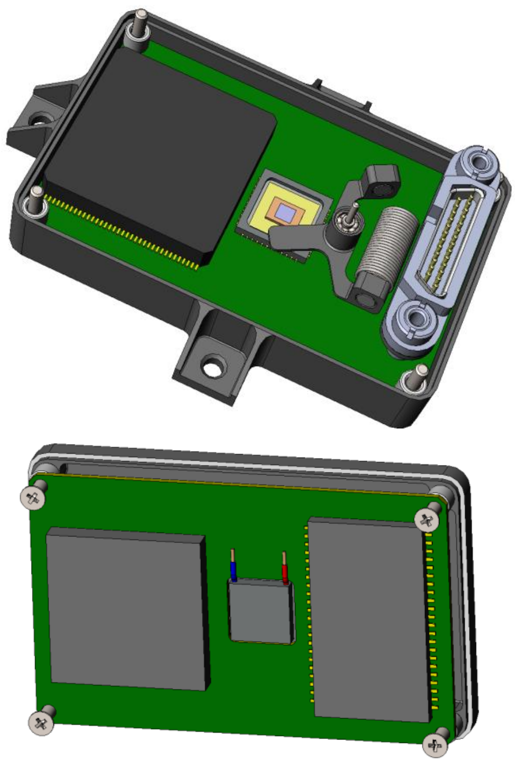

Figure 5: Top and bottom view of the STC printed circuit board

Any subsequent processing of a noisy image cannot decrease attitude error, which may be quite high. It is possible to suppress this error only by increasing the detected stars' signal.

At the same time, a number of systematic errors are also present in star trackers. In contrast to random ones, these errors depend on the set of parameters and, in principle, can be reduced by appropriate processing of images.

Unreduced systematic errors combined with random ones lead to significant increase in total effective noise. As we justified ealier[3,4] the accuracies of modern star trackers are about 10–30 times worse than that defined by only random noises. Indeed, merely pixel-to-pixel inhomogeneity of dark currents decreases attitude accuracy up to 3–4 times[4].

Typical design of modern star trackers does not allow taking such systematic errors into account. The main problem is necessity of complex image processing procedure, which requires more flash and operative memory. And this concerns both small and "big" star trackers.

In contrast, the STC design assumes a reduction of a set of systematic errors. Namely, we developed algorithms which reduce:

- inhomogeneity of sensor's dark currents (including "hot" pixels);
- inhomogeneity of sensor's pixel response;
- differences in gain of amplifiers;
- lens aberrations: both chromatic and achromatic.

SPECIALIZED CHIP FOR STC

In our project "Star Tracker on Chip" we intend to design a specialized chip for star tracker's image processing. The processing algorithms we assume to use are more complex than the ones for ordinary trackers. With this chip one will be able to decrease the tracker's cost, weight and size. Also, such chip may be combined with a CMOS photosensor with the purpose of miniaturization.

The processes of developing and testing of such chip is quite expensive and complex. Therefore, our experimental series of STC will use FPGA (Field Programmable Gate Array) instead.

CALIBRATION OF STC

Ground-based calibration

To correct the systematic errors mentioned above, the information about sensor's pixel-to-pixel sensitivity variations (so called "flat field"), dark current map and lens aberration polynomials must be stored in the tracker's flash-memory. These data can be obtained from particular ground-based calibrations and are unique for every individual STC.

On-orbit calibration

Properties of a photosensor tend to change in the conditions of outer space, mostly due to impact of high-energy particles. Pixels' sensitivities change, dark currents increase and new hot pixels appear. So, the results of ground-based calibrations stored in the tracker's memory become less and less actual.

As a result the tracker's total systematic error increase and, hence, its attitude accuracy degrades. Nevertheless, this problem may be fixed if new calibration data are obtained during the flight. The idea of on-orbit calibrations was already discussed by several authors[5,6], but specific STC calibrations significantly differ from the described in those papers.

To improve stored map of dark currents, a number of dark frames (with enclosed lens) must be obtained. Then, the relative pixel-to-pixel sensitivity can be calibrated using images of the uniformly illuminated sensor (e.g., by white light-emitting diode illuminating the lens). The lens of the tracker during this procedure must be also shuttered from the outer radiation.

The enclosing of the lens is assumed to be realized with using mechanical shutter introduced into STC design. This feature may decrease device reliability. However, no such calibration procedure is known to the authors, where lens assumed to be open. So, for on-orbit calibration, STC must be provided with a shutter as it shown in Figure 5. (Additional source of light, used for sensitivity calibration, is not shown in this Figure).

CONCLUSION

Weight and sizes of STC tracker allow using it with the micro- and nano-satellites of a different kind. Moreover, parameters of STC (and, especially, of STC-2) make it a possible equivalent to usual "big" star trackers.

Ability of on-orbit calibrations provides a long term preservation of high attitude accuracy.

ACKNOWLEDGMENTS

The work was partially supported by Ministry of Education and Science of Russian Federation in frame of agreements 8059 and 8239.

Authors express gratitude to «Skolkovo» Innovation Fund for their help and support of «Star Tracker on Chip» project.

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