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DESIGN AND DEVELOPMENT OF THE OPTICAL SYSTEM FOR THE NANOSATELLITE USING RAPID MANUFACTURING

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Abstract: *An international team of Master's students from the Tallinn University of Technology in cooperation of MEKTORY Space Center design a unit size nanosatellite for camera based low Earth observation mission. It is important that image acquired with the optical system of the satellite stays in focus even during thermal expansion and after possible deformations caused by vibration or thermal shock to obtain clear image. Proposed solution allows adjusting the focus and locking lens into place avoiding misplacement at launch sequence vibrations and separation shock.*
Mirror and mirror mount are also to withstand similar conditions. Both mirror and lens are contained in a special casing that provides protection against contamination and a frame protects the sensor from possible vibrations. Problem of stray light in optical systems was also investigated and solutions appropriate to space application is chosen and implemented.

Key words: Nanosatellite, Optical System, Image, Line scan sensor, Low Earth Orbit.

1. INTRODUCTION

The Optical system for the Nanosatellite required design that could withstand the extreme conditions of space. In order to meet the needed standard, required calculations were made and parts as well as their materials were carefully chosen. The best coating solution was also proffered and the prototype was manufactured. The result of this stage of the project gives the needed confirmation to proceed with the design for integration of the optical system into the full system of the Nanosatellite.

2. DESIGN OF THE OPTICAL SYSTEM

2.1 Depth of Focus

Depth of focus is a tolerance in the length from the lens to surface of the sensor, where focus of the resulting image remains acceptable.
There are many ways for estimating the depth of focus. A formula used in astronomy was chosen for the estimate.
Depth of focus is estimated with the following formula:

$$\Delta f = \pm 2\lambda N^2 \quad , \qquad (1)$$

where:
Δf – depth of focus,
λ – wavelength,
N – lens f-number. [1]

The shortest wavelength for this optical system is 400 nm so the estimated depth of focus is.

$$\Delta f = \pm 5 \cdot 10^{-6} m$$

Test conducted on the first prototype showed the tolerance, in which there is no appreciable drop in image quality to be much larger. This can be attributed to the specific qualities of the combination of sensor and optics. The final Δf determined to be:

$$\Delta f = \pm 5 \cdot 10^{-4} m$$

2.2 Choice of Material and Details of Design

Choosing materials requires consideration of four main aspects. Thermal expansion, material approval for use in spacecraft, outgassing and weight.

For the optics design proposed, the preliminary estimation of maximum variation in depth of focus is

$$\Delta f = \pm 2\lambda N^2 = \pm 10^{-4} m$$

Temperature variance the satellite has to cope with is Δt= ± 200 ℃. The nominal value for focal distance is $f_{nom}=3{,}39\cdot10^{-2}$ m

From these limits the maximum coefficient of thermal expansion for the material must be less than $L_t=7{,}37\cdot10^{-5}$ m/m/ ℃. This criteria fits many materials.

List of approved materials for construction of the CubeSat is based on the NASA-STD-6016 standard. An important measure of performance is outgassing. Outgassing is a property of a material to release trapped gases and debris when put in a vacuum and heated. NASA technical manual "Outgassing data for selecting spacecraft materials" is the basis for outgassing information.

Two main options for addressing this criterion are choosing a material from the approved list or testing the chosen material according to the appropriate testing procedure. Less time consuming and cost effective is to do without testing and choosing an approved material. This criterion diminishes the suitability of additive manufacturing techniques, including SLS (Selective Laser Sintering). Even though a base material, for example aluminum 6061 is selected from approved materials list, the process of SLS introduces a high likelihood of trapped gasses and debris.

6061 aluminum alloy is the material for satellite frame and also fills all the main criteria.

Coefficient of thermal expansion for 6061 alloy is $L_t=2{,}35\cdot10^{-6}$ m/m/ ℃. Density for 6061 alloy is 2700 kg/m^3. [2]

This gives the aluminum parts final weight of 47g and maximum thermal expansion in the optical path

$$\Delta f = \pm 1{,}56\cdot10^{-4} m$$

A lot of modifications were made. Starting from the dimensions of the optical system section floor which was at maximum point 100x100x50 mm. After which it was found out that there was even less space to fit into, because of the electronics PCB board that needed 40 mm more space for cables and taller components. Material choice that was appointed by mechanics team was Aluminum 6061 in chemical form AlMg1SiCu according to EN573 standard. Aberrations also had to be considered while making the right component design that suited our requirements. Thermal expansions had to be considered, because it could affected the parts dimensions cosine misalignment and aberrations within the system. Choice of the right lenses for the system. Also decision on the right manufacturing methods, tolerances and surface roughness.

Before integrating the final design into the complete assembly of the nanosatellite, a simple version of the solution was made using rapid prototyping. Simplified model was made from materials that Tallinn University of Technology had provided. We took PE and POM plastics, because they are fairly strong, similar at strength to aluminum, easy to handle and the cutting edge of the blade is preserved during milling.

Rapid prototype was used to make different tests and to understand if the concept solution was right. Big challenge was to fix mirror at the right place with the mirror mount that could withstand vibrations without moving mirror to maintain right focal length. Solution was to make metal spring that will be milled and bent according to mirror dimensions.

The mirror used was made from fused silica, having a low thermal expansion coefficient of $0,52\cdot10^{-6}$/°C, The 19 mm diameter, 6 mm thick mirror has surface flatness λ/10 at 632,8 nm over clear aperture. However light with wavelength of range 450 nm to 20 µm can be reflected using the mirror. The mirror is mounted to reflect the incident light at an angle of 45° to the sensor. The low thermal expansion of the mirror gives an advantage considering the thermal variation in space, the fused silica material will ensure that the image reflected to the sensor is not distorted. In order to accommodate for the vibrations during launch, the mirror is secured to the optical compartment with a leaf spring which also behaves favorably under thermal variations. The leaf spring also accommodates the little expansion that may be transferred from the mirror.
For leaving the right spare material to compensate for the material compressed during bending, the bend angle calculation had to be made by DIN 6935 (1975-10) standard.

$$v=2\cdot(r+s)\cdot\tan\frac{180°-\beta}{2}-\pi\cdot \cdot\left(\frac{180°-\beta}{180°}\right)\cdot\left(r+\frac{s}{2}\cdot k\right), \quad (2)$$

where:
r – radius 8,268 mm,
s – sheet metal thickness 0,5 mm,
β – bending angle 51,18 º,
k – correction factor,
v – spare of material.

First the correction factor had to be calculated by using formula:

$$k=C+A\cdot\log\frac{r}{s}, \quad (3)$$

where:
constant C = 0,65,
A = 0,5,
k=1,26,
v=17,31 mm.

The calculated value helped to design spring flat pattern and bend spring correctly.
Lens had to gather all the light on the sensor, so it was decided to cut lens empty part off making it shorter. As result gathering more light and be easier integrated to the design concept. By calculations 2,013 W/m^2 light radiance will reach the sensor.
The lens holder had to be easily adjustable and fix the lens strongly in place to ensure invariable focal length. Also it had to be strongly fixed to the base plate. At first the lens holder was planned to be 3D printed, but the tolerances of the 3D printing was ±0,15 mm and it does not suit our needs. So the milling was chosen for this aluminum part manufacturing with tolerances of ±0,0016 mm

In agreement and collaboration with the PCB team, we came with the idea of constructing a frame support between the base plate of the system and the PCB where the sensor is located. This frame is important, because it not only gives the support between the layers during vibration but also serves as a protection capsule for the most fragile element, the sensor.

The base is also constructed in such a way to support the whole lens system. It will also be connected to the frame of the Satellite.

To protect system from the dust, connect lens and mirror special casing was made. This component has an important role of for the system that's why it is also manufactured also from aluminum using milling machines with tolerances ±0,0016mm DIN EN ISO 1302 (2001-06).

For the final design no major changes were made. The design concept we chosen for first prototype was used to make final model. Most of the model components are made from Aluminum 6061 (Base plate, lens holder, dust shielding) and milled by milling machine by DIN EN ISO 1302 (2001-06) standard. Fixation is still done by M3 bolts with non-magnetic properties. The base plate is made bigger for easier fixation to the mane satellite body and some extra cut outs for the cables were made. The part that was added is lens hood.

Information about tolerances and standards were taken from the book "Mechanical and metal Trades Handbook" [3]

The final design is shown in the figure below.

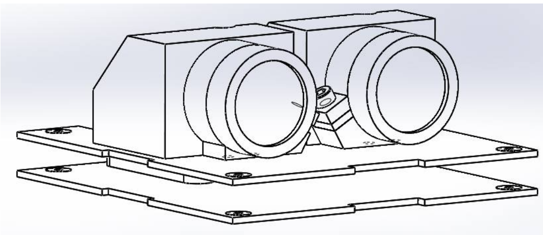

Fig. 1. Final Prototype of Optics Chamber

2.3 Minimizing Stray Light in Cameras with the Help of Light Absorbing Coating

Stray light are light that are not intended to enter the optical system. These light interfere with the useful light and reach the image sensor, thereby producing noise.[4] These stray light must be eliminated by either reflecting them out of our system or by absorbing them or by scattering them before they reach the image sensor. By doing so we can improve the quality of the image produced. This reduction can be accomplished with the help of light absorbing coatings or by using baffles.

The coatings are used to form lambertian surfaces on top of the aluminum alloy 6061 used to construct the optical system. When a stray light falls on a surface with lambertian properties, it gets scattered in all directions thereby the intensity reduces a lot and hence the noise is reduced. In non-technical terms light is said to be absorbed. This effect can be achieved with the help of coating that is applied on the interior surface of the camera. The type of coating used should be such that it satisfies the criteria for spaces application.

2.4 Criteria to Consider for Space Applications

2.4.1 Temperature Resistance

Assume a metal plate placed on the lower earth orbit, its temperature will vary from -170°C to 123°C, [5] and it will get to its positive extreme when it is facing the sun and the negative extreme when no light falls on it. This will make the metal contract and expand repeatedly and this may affect the coating to wear off or produce dust inside the optical chamber which is counterproductive to the aim of the coating. Hence the coating technology chosen should be able to withstand these extreme temperature conditions.

2.4.2 Vibration resistance

During the launch and its journey to the lower earth orbit, the optical system will be subjected to various shocks and vibrations due to gravitational forces and the rocket propulsion systems. These can also affect the coating applied. So the coating should have good adhesive qualities so that it can withstand these conditions.

2.4.3 Outgassing

Outgassing refers to gas molecules trapped inside the coating that may escape out when there is enough pressure difference. Gas molecules may also form due to some chemical reactions inside the coating. During the process of escape, this gas can remove a piece of coating along with it which may float around in the optical chamber and produce noise due to the weightless environment of the lower earth orbit. The European Space Agency has set several standards to measure the outgassing, two of which include CVCM, WVR, RML and TML. So the coating chosen should satisfy these standards set by the ESA.

2.4.4 Carbon Nanotube Coating (CNT)

This technology was first introduced by NASA in the SPIE optics and photonics conference. This type of coating is made up of thin layer of hollow carbon nanotubes with multiple walls of pure carbon. The layer has millions of these tiny tubes and each tube is about 10 000 times thinner than human hair. They are arranged vertically like a tall shag rug/carpet. [6]

It works by trapping light between the walls of the nanotubes and between adjacent nanotubes.

These coatings have very low reflectance of less than 1 % in the wavelengths of interest in the visible and IR range which is 150 nm to 1500 nm.

2.4.5 Advantages over Anodized Black Coating, Paints and Powder Coats

-On an average the conventional coating processes can only absorb 90 % … 97 % of incoming light.

-They do not remain black at all temperature. When they get cold they take a shiny silver color.

-Black paints have radiative properties at longer wavelength

-To prevent these radiative emissions epoxies are loaded with conductive metals to create a black coating.

-This adds weight which is an undesired quality for space applications. [6]

3. CONCLUSION

Using rapid manufacturing, the optical system for the Nanosatellite was designed and developed. This design is ready to be integrated into the whole Nanosatellite system.

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