Solar sensor for Cubesat attitude determination

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***Abstract*—This article addresses a design and implementation of sun sensor for the attitude determination system of a nanosatellite. The purpose of the sun sensor is a determination of the coordonnees of the "satellite-sun" vector in the reference frame attached to the satellite. This is done by processing the photovoltaic signals issued from the solar sensors placed on the 6 sides of the satellite. The article presents a mathematical model of the sensor, the characteristics of the chosen solar panels, the methodology of calibration and details of the hardware and software implementation. The operability of the system is validated by a laboratory experiment, whose methodology is presented in details. The proposed algorithm of the sun sensor addresses the processing of the Earth albedo and the self-calibration aspects.**

***Index Terms*—nanosatellite, sun sensor, coordinate, vector, mathematical model, experiments.**

I. Introduction

Satellite technologies are an essential component in the study of outer space, as well as for many other tasks. Along with large-budget ambitious spacecrafts, nanosatellites (further NS) in the Cubesat format has recently appeared as a realistic low-cost alternative for average complexity space missions [1]. Due to the low cost and availability of technical solutions, the launch of a NS allows one to conduct various scientific experiments regardless of the possible carriers of the device (large research satellites, etc.) and without requiring large funds and resources.

Solar panels on the NS are mainly used for electrical energy generation. However, they can also be used for satellite attitude determination, since they may provide information about the sun position with regard to the satellite [2] [3] [4] [5].

The aim of the sun sensor is to provide the coordinate of the vector "sun-satellite" in the reference frame *Sat* related to the satellite. If the position of the satellite on the orbit is known – this is usually the case – from the Sun and Earth ephemerides it is possible to identify two of three components of the attitude of the satellite. When other attitude sensors are used, for instance, the magnetic field sensor identifying the magnetic field vector in the *Sat* frame, the full satellite attitude may be defined. Such a low cost attitude determination system may be highly useful for small university satellites in the Cubesat format (figure 1), where more expensive attitude determination mechanisms such as stellar sensors may not be accessible.

This article provides details on the design and the practical implementation of a NS sun sensor which use the main solar panels of the satellite. It can be easily adapted to more compact solar sensors specially devoted to the attitude determination, placed alongside with the main solar panels. However, in the low cost small satellites, solar panels may be used both for the attitude determination and for the power generation through a time division multiplexing [6].

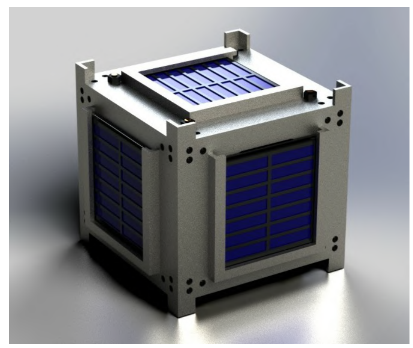

Fig. 1. Cubesat model.

The article is organised as follows. Sec. II-A presents the operation principle of the sun sensor and its mathematical model. Sec. II-B presents the self-calibration methodology of the sun sensor. Sec. II-C presents the used photovoltaic panel and their characterization. Sec. III describes the hardware implementation of the sun sensor. Sec. IV presents the experimental results.

II. Sun sensor architecture and model

This chapter describes how the physical quantities measured on solar panels are used for determination of the satellite attitude. First, we present a mathematical model of the sun sensor. Then we present the characterization results of the solar panels used in this project.

A. Mathematical model

In this model, we suppose that the NS coordinate system is aligned to the NS facets, so that each facet is identified by its normal axis (x, y or z) and by the sign. By convention, if the axis crosses the face from the inside to the outside of the satellite, the sign is +, otherwise the sign is -. Alternatively, for mathematical commodity, we attribute a number from 1 to 6 to each facet.

The output information of the sensors is presented in the form of six analog currents or voltages, each signal having the same index as the corresponding facet. The electrical signal generated by each sensor depends on the incidence angle of light on solar panels: This angle is defined between the sun-satellite vector and the normal vector of the panel, which coincides with the unity vectors of the corresponding coordinate axis with signs + or -. The incident power is proportional to the cosines of the incidence angle.

If the current generated by each panel is proportional to the incident power, by measuring the value of the currents from each panel, one can determine the incidence angle α_i using the formula (1):

$$I_i/I_0 = \cos\alpha_i, \tag{1}$$

where I_0 is the maximum current of the panel (when the incidence is 0°), I_i is the measured value of the current. We note that $\vec{n_i}\cos\alpha$ gives the the projection of the sun-satellite vector $\vec{n_{ss}}$ on the normal vector $\vec{n_i}$ of the panel i. The incidence angle takes values within $[-\pi/2, \pi/2]$. Other angles correspond to the sun illuminating the satellite behind the given panel, and so, no light is received by the panel. In this case the incident power from the sun is zero, although the panel may be enlighted by other sources (Earth, Moon) – this will be discussed in sec. II-B.

Given that, there are only three possibilities: only one panel exposed to the sun, two adjacent panels exposed to the sun, three adjacent panels exposed to the sun.

If only one panel is exposed, the problem is trivial: the sun-satellite vector $\vec{n_{ns}}$ is the same as the normal vector of the exposed panel (fig. 2a):

$$\vec{n_{ns}} = \vec{n_i} \tag{2}$$

If only adjacent two panels with indices i and j are exposed, from fig. 2b it can be seen that the sun-satellite vectors is a vector sum of the projection of $\vec{n_{ns}}$ on the normal vectors of the panels. We have:

$$\vec{n_{ns}} = \vec{n_i}\cos\alpha_i + \vec{n_j}\cos\alpha_j \tag{3}$$

In the most general case, three panels with indices i, j, k are exposed. By analogy with the previous case, one can write:

$$\vec{n}_{ns} = \vec{n}_i\cos\alpha_j + \vec{n}_j\cos\alpha_i + \vec{n}_k\cos\alpha_i \tag{4}$$

It can be seen that the formula(4) is also valid for the two other cases, since non-illuminated panels produce a zero current. Moreover, one can generalize eq. 4:

$$\vec{n}_{ns} = \sum_{i=1}^{6} \vec{n}_i\cos\alpha_i \tag{5}$$

B. Calibration of the measurement and the Earth albedo

The proposed mathematical model supposes to know the current I_0 generated by a panel when the panel is fully exposed to sun ($\alpha = 0$). This current cannot be precisely known in practice. Aging of the solar panels make it difficult to pre-program the value I_0. However, one can take advantage of the fact that the total incident sun power on the orbit can be

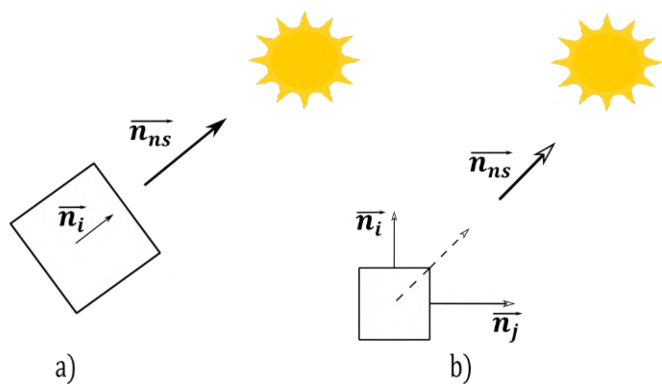

Fig. 2. Construction of the sun-satellite vector in the case where the sun illuminates only one facet (a) and only two facets (b).

considered constant, so is I_0. Since we have $\sum_{i=1}^{6}\cos\alpha_i^2 = 1$, a simple calibration can be performed:

$$I_0^2 = \sum_{i=1}^{6} I_i^2 \tag{6}$$

and the vector $\vec{n}_{ns}$ can be obtained by:

$$\vec{n}_{ns} = \frac{\sum_{i=1}^{6}\vec{n}_i I_0}{\sum_{i=1}^{6} I_i^2} \tag{7}$$

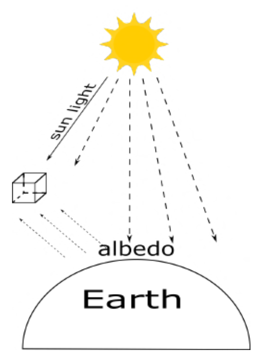

Fig. 3. Earth albedo and the sun vector determination.

This model does not account for the Earth albedo, which is the reflection of the sun light by the Earth, which can represent up to 30% of the incident solar energy (fig. 3). If the satellite is exposed to the sun and to the Earth albedo, the equation (6) is wrong. In practice it is relatively easy to isolate the albedo effect, since the same facet is never exposed at the same time to the both, and there always one, two or three adjacent faces exposed only to the sun, so that the sum of the square of theirs currents is constant. An easy solution consists in building 8 variables (one for each vertex):

$$S_{ijk} = I_i^2 + I_j^2 + I_k^2 \tag{8}$$

where i, j, k are the indices of adjacent facets, and to identify for which vertex this quantity is maximum: this vertex will probably be that facing sun, so that the current value measured from non-adjacent facets can be ignored (zeroed).

C. Solar panel models

Solar panels convert the solar radiation energy into the electricity. The solar panel modules are manufactured from pseudo-square mono-silicon or square poly-silicon photo-voltaic converters (FEPs) coated with an anti-reflection material. For the study, Poly-crystalline Silicon Solar Panels were used. Table(I) below shows the main characteristics of these panels.

TABLE I
CHARACTERISTICS OF SOLAR PANELS.

N°	*name*	*indications*
1	Material	Poly-crystalline silicon
2	Size	60×60mm
3	Voltage	5.5V
4	Maximum current	80mA

For the laboratory experiments, the sun was emulated with a halogen spotlight from the company Valex having power $300W$. In order to prepare the design of the electrical blocks of the sun sensor, a current-voltage characterizes of the panels was measured at room temperature. The result is shown in Figure 4. During the measurement the solar panel was exposed normally to the light source at distance of $30cm$.

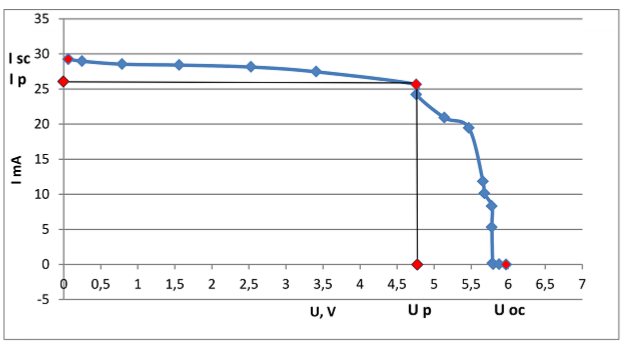

Fig. 4. A current–voltage characteristic of the solar panel.

This graph provides an information of the generated power as the function of the load current or voltage. From this graph it can be seen that the solar panel behaves as a close-to-ideal current source, so that the short circuit current may be used for measuring the illumination of the panel. One should note that for semiconductor solar cells, the open circuit voltage decreases by 0.4% when the cell temperature increases by 1°C. At the same time, the values of the short-circuit current increase by 0.07% when the temperature increases by 1°C [1].

After determining the characteristics of the solar panel, we investigate the influence of the angle of incidence of light on the panel's short circuit current. The experiment was carried out under the following conditions Figure5:

- The distance from the solar emulator and the solar panel is 34 cm;
- Room temperature 20°C;
- The panel rotation step is 5°;
- Load resistor 27.2 Ohms (short circuit condition).

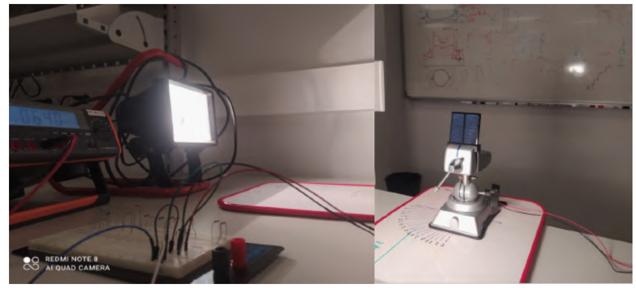

Fig. 5. The process of conducting the experiment.

Fig. 6 presents the plot I versus the cosines of the incidence angle, from 0 to $[-\pi/2]$.

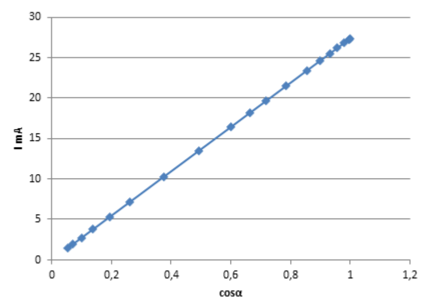

Fig. 6. Panel's short circuit current versus cosines of incidence angle.

The obtained data are consistent with the theory exposed in II-B and II-A, and confirms the possibility to use the proposed methodology for the sun sensor identification.

III. Sun sensor implementation

To determine the satellite-sun vector, the *Arduino® Mega 2560* board is used [7]. The *Arduino® Mega 2560* has several analog inputs interfaced with a 10 bits ADC operating at a frequency of $16MHz$. Since the ADC receives a voltage at its input, the short circuit current should be converted to voltage with a small value resistance R_L.

The set-up of the measurement scale is done by properly choosing the ADC full-scale voltage and the resistance R_L. The full-scale voltage of used ADC is equal to its reference voltage. In order to maximize the dynamic range of the measurement, the reference voltage needs to be close to the maximum measured voltage. In this design, we chose the built-in reference voltage of $1.1V$, which is stable and does not depend on supply voltage and temperature. The resistance scaling the output voltage R_L was chosen accordingly, so to have $I_0 R_L$ close to the reference voltage (here I_0 is the maximum current of the solar panels).

The sampling frequency is set by programming the register $ADCSRA$ which sets the frequency division coefficient of the ADC clock frequency of 16 MHz. The division factor of 16 was chosen. One analog conversion takes 13 clock periods. This yields the sampling rate calculated as: $16MHz/(16*13) \approx 77kHz$. The result of the analog-to-digital conversion is read into the *ISR* interrupt processing function *(ADC-vect)*. The 10 bits output value is read in two 8 bits registers *ADCL* and *ADCH*. To obtain more accurate results, an internal reference voltage was used. Which can be connected using the command code as follows $(analogReference(INTERNAL1V1)$, that is, the output outputs a maximum voltage equal to $1.1V$. It is possible to measure the voltage from 0 to 1.1 Volts with an accuracy of $1.1/1024 = 1.01$ mV.

Since the attitude dynamic quantity are related to the motion of the satellite and vary slow, the photovoltaic current is close to be constant. Hence, a low pass filtering is necessary in order to remove measurement noise. This is done through a software digital filter.The arithmetic mean filter was chosen. The arithmetic mean is a FIR (Finite Impulse Response) filter described by the equation:

$$y_n = \frac{1}{N} \sum_{k=0}^{k=N-1} x_{n-k} \tag{9}$$

where N is the depth of the mean filter, x are y are the input and the output quantities respectively. For this implementation, N=150.

After setting up the ADC scaling and the noise filter, the hardware was programmed to determine the NS-sun vector. Figure 7 shows the functional diagram of the system. The outputs of the solar panels are measured by the ADC sequentially using a built-in multiplexer. The measured values are then processed in an arithmetic block according to the algorithm presented in sec. II-A. In order to filter out the albedo effect, the algorithm presented in sec. II-B was used.

IV. Experimental results

The described sensor has been implement and tested. For practical reasons related to the laboratory test, only 5 panels were installed on the nanosatellite.

The experiment was conducted as follows. The satellite is mounted on a three-axis holder at a distance of 32 cm from the sun emulator. The first experiment is when the sun's ray falls only on one side of NS. The program calculates the cosine of the angles between the solar panels and the satellite-sun vector using the formula 7. Below in the figure 8 it can be seen that the angle of incidence of the beam on the x+ panel is 90 degrees. The displayed data show that $\vec{n}_{ns} = \vec{n}_{y+}$, where $\vec{n}_{y+}$ is the normal vector of the $y+$ panel.

In the second experiment, the sun illuminates two sides of the satellite. We made two experiments: one when the two panels are illuminated equally (the incidence angle is 45°, figure 9) and one where two panels are illuminated unequally, figure 10. In both cases, the sensor correctly identifies the angle of incidence of the beam, with the help of this data we can find the coordinates of the vector $\vec{n}_{ns}$. For instance, for the case of fig. 10, we have $\vec{n}_{ns} = 0.86\vec{n}_{x+} + 0.51\vec{n}_{y+}$

The third experiment represents the most general and frequent case, when the sun illuminates three panels. Two

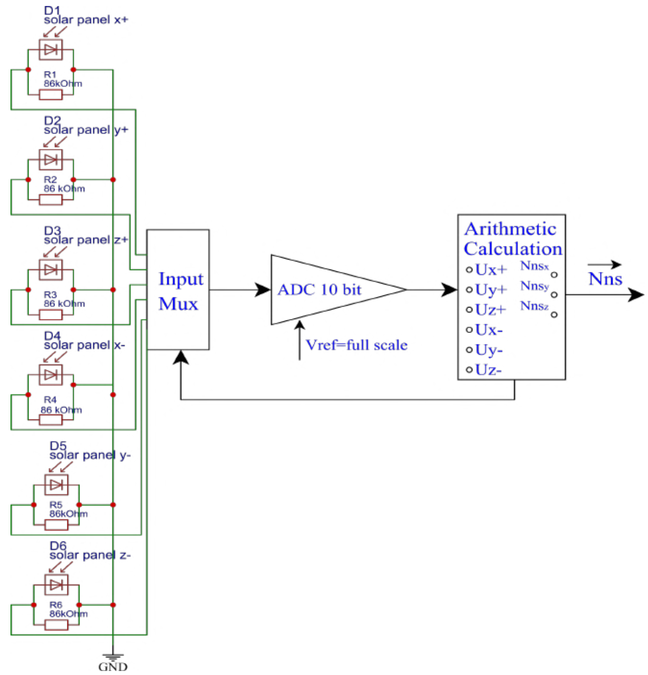

Fig. 7. Functional scheme of the system.

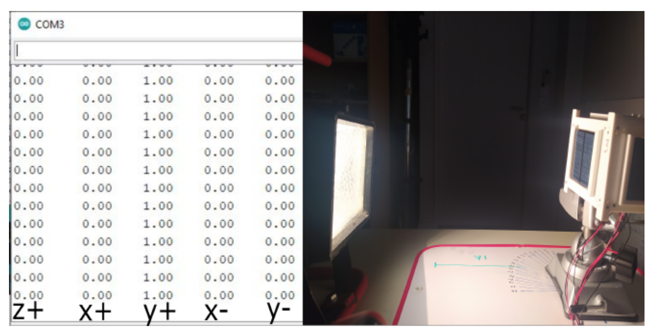

Fig. 8. Measurement of the cosine of the angle per one side of the satellite.

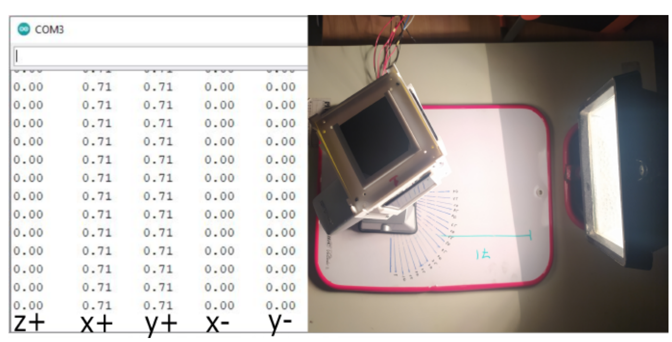

Fig. 9. Readings of the beam incident sensor on two sides of the satellite.

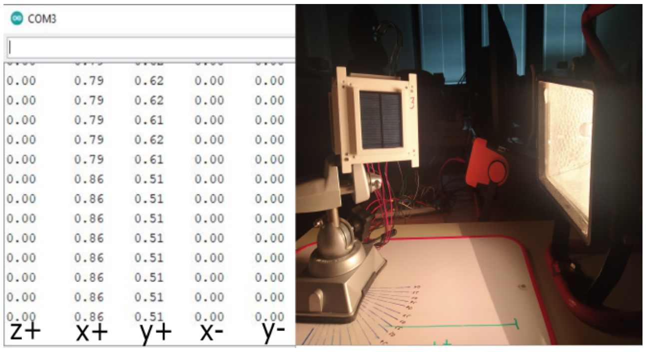

Fig. 10. The incidence of a sun ray on two faces of a satellite at different angles.

experiments was made: one when the sun illuminates equally the three panels (the incidence angles are α=60.8°) (Figure11), and one case where the one of the panels is illuminated at a different angles (figure 12). In both cases, we receive correct data from the sun sensors. For instance, for the second experiment we have $\vec{n}_{ns} = 0.67\vec{n}_{z+} + 0.67\vec{n}_{x+} + 0.32\vec{n}_{y-}$

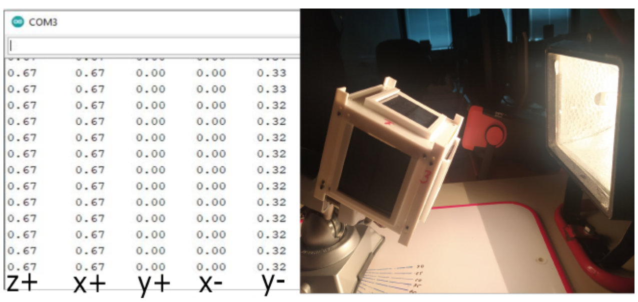

Fig. 11. The readings of the beam incident sensor on the three sides of the satellite.

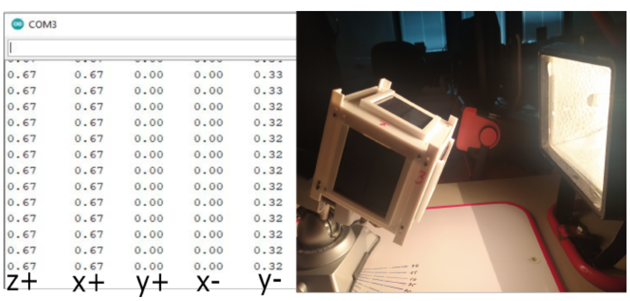

Fig. 12. Readings of the beam incidence sensor on three sides of the satellite at different angles.

V. Conclusion

This article reported on the design, implementation and laboratory test of a low cost sun sensor compatible with nanosatellites of Cubesat format. The Sun sensor identifies the coordinates of the vector ”Satellite-Sun” in the satellite reference frame; this data is used for the satellite attitude determination. The developed mathematical model includes the effect of the Earth albedo on the sun sensor.

A sun sensor allows an attitude determination only on two axes. For full attitude determination, the sun sensor may be complemented with a magnetic field sensor: that yields in a simple and low cost attitude determination system.

The sun sensor operates only at the orbit day (when the sun is present): That limits its application to the mission where the satellite orientation must be controlled only during the daytime, typically, in the cases where the mission consists in the photography of the illuminated Earth surface.

The article presents all practical information about the sensor implementation and provides the results of the experiment carried out in the laboratory conditions.

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