Low-Cost Design and Development of 2-Axis Digital Sun Sensor

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Abstract— Sun Sensor is a commonly used sensor in satellites for attitude determination. This paper discusses the design and development of 2-axis digital sun sensor (DSS) using commercial-off-the-shelf (COTS) components. The CMOS linear array based simple design of DSS, having a field of view of ±45°, has been implemented with a Sun angle determination accuracy of 0.5°. Three such sensors mounted appropriately on satellite's platform can determine the sun angle in normal conditions. The design offers a low-cost and power efficient solution for micro-satellites.

Keywords— Digital Sun Sensor, DSS, linear CMOS array, Attitude Determination

1 INTRODUCTION

Sun Sensor is the most common sensor used in satellites for attitude determination. [1] The Analogue sun sensors, although being simpler in design, suffer from the problem of low accuracy. Digital Sun sensor is a better choice where attitude determination scheme demands higher accuracy for a large field of view. [2] Although being accurate, the Digital Sun Sensors available are complex in design, expensive and at times bulky and power inefficient. The designed CMOS linear array based digital sun sensor, being simpler in design, provides a light-weight, low-cost and power efficient solution for use in micro and small satellites.

In the coming paragraphs, working principle of the sensor has been discussed. Later sections provide details on the accompanying processing electronics that generates the driving signals and processes the output bit stream to identify the maximum highlighted pixel. A brief description of the DSS housing is followed by a discussion of the sun vector determination algorithm. Finally calibration and test results are presented along with the technical specifications of the DSS.

2 LINEAR VS. 2D ARRAY

CMOS based Digital Sun Sensors are designed using both linear and two dimensional arrays as image sensors. A mask is placed above the image sensor at a certain height having tiny slits or pinhole apertures through which sunlight passes to illuminate different pixels from which the sun angle can be extracted. Accuracies thus achieved vary depending upon the optical design and the algorithm used to process sun images. See for example [3-6].

Although the designs utilizing a 2D array offer better accuracy, they impose more processing requirements upon the system. The number of pixels to be sensed is multiplied which in turn mitigates the update rate of the sensor. Moreover in order to obtain the desired update rate the processing unit has to be upgraded adding complexity to the design and increasing power requirements. On the other hand use of linear arrays permits simple design and better response time.

2.1 Working Principle

Figure 1 shows the working principle of a CMOS linear array based digital sun sensor. The linear image sensor is placed beneath an opaque layer having a thin slit in such a way that the centre pixel of the sensor lies directly under the slit i.e. a line joining the slit and the centre pixel will be perpendicular to the active region of the sensor. The distance (h) between the CMOS array and slit defines the field of view.

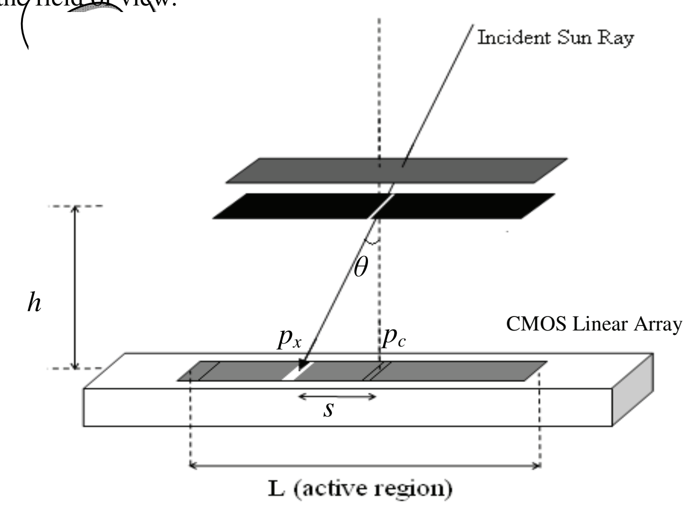

Figure 1 - Working Principle of CMOS Based DSS

Light entering through slit illuminates different pixels depending upon the angle of incidence.

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Knowing the distance (s) of illuminated pixel from the centre pixel and the height (h) of slit enables us to calculate the angle (θ) as follows: [3]

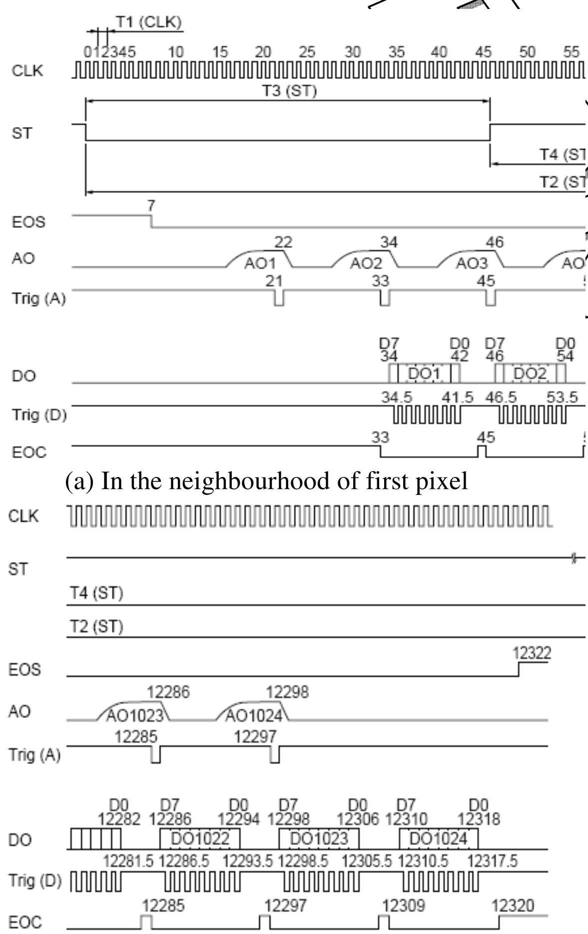
$$\tan(\theta) = \frac{s}{h} \qquad (1)$$

$$s = k(p_x - p_c) \qquad (2)$$

Where k = pixel spacing
p_x = illuminated pixel
p_c = centre pixel

3 PROCESSING ELECTRONICS/ SCHEMATICS

Two 1024 pixels CMOS linear image sensors are used in the design. The used CMOS provides both the analogue and 8-bit digital values of all 1024 pixels in every scan cycle. Figure 2 shows the timing diagram of the CMOS linear image sensor.



(a) In the neighbourhood of first pixel

(b) In the neighbourhood of last pixel

Figure 2 - CMOS line sensor timing diagram

Block diagram of the schematics is shown in figure 3. Upon receiving request from the AOCS (Attitude and Orbit Control Subsystem) computer, the controller performs a sequence of following operations:

- Generation of timing and control signals for both the CMOS sensors
- Storage of data received from both the sensors (8-bit digital values of 1024 pixels from each sensor)
- Calculation of angles after determining the maximum highlighted pixel
- Determination of the sun vector in sensors body frame from the calculated angles
- Transmission of vector components and/or digital values of all pixels over CAN module/ serial interface to AOCS computer or Telemetry interface

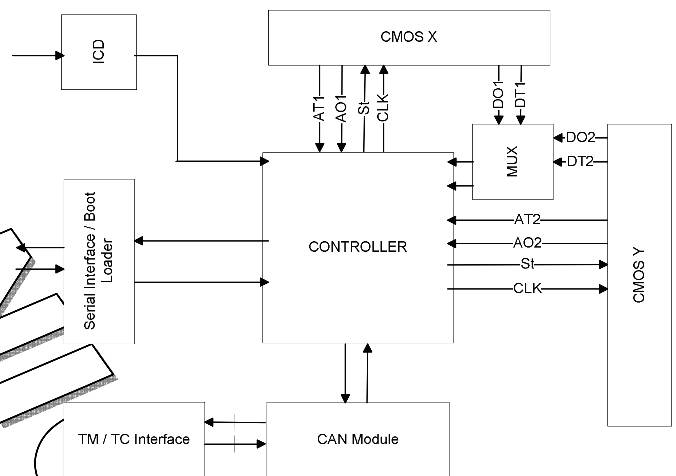


Figure 3 - Block diagram of the Digital Sun Sensor Schematics

The sensor can yield output at the frequency of 2Hz. Moreover an In-Circuit Debugger (ICD) and serial interface have been provided for programming /testing/debugging purposes.

4 PHYSICAL CONSTRUCTION

In order to determine three components of the sun vector in body frame, two spatial angles must be measured; hence two linear image sensors are used. The design is such that the two mutually perpendicular linear arrays lie on one side of the circuit board while rest of the processing circuitry lies on the other side (see figure 4).

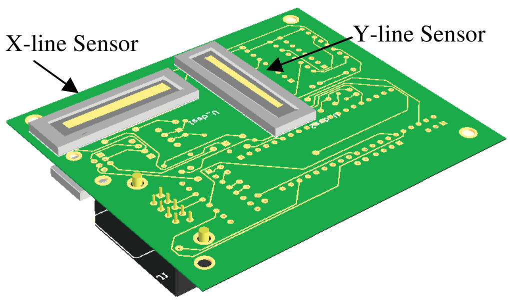


Figure 4 - A 3-D view of the DSS board showing mutually perpendicular linear image sensors

The housing has been made of aluminium alloy. The opaque layers with slits are directly above the linear arrays, and have been accommodated in the lid of the sensor's housing. CAD drawing of the housing is shown in figure 5.

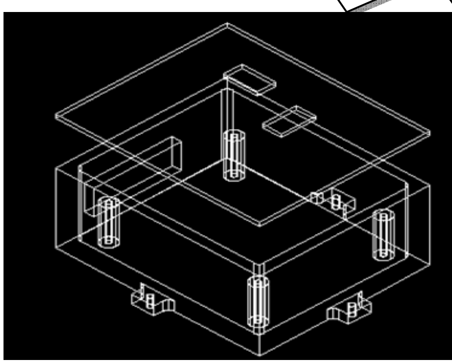


Figure 5 - CAD drawing showing an isometric view of the DSS casing

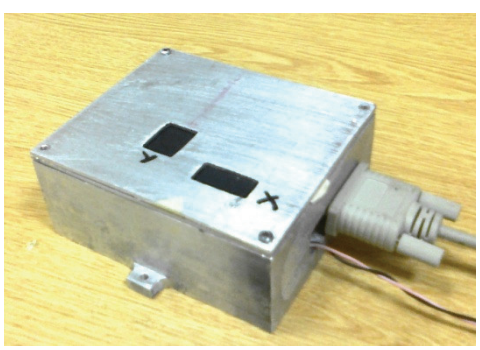


Figure 6 - Developed Digital Sun Sensor

5 Sun Angle Determination Algorithm

The Sun vector is determined by measuring 2 perpendicular angles, α and β; made by the projections of sun vector on XZ and YZ planes with the Z-axis [7], as shown in figure 7, where XYZ constitutes the body frame of the DSS.

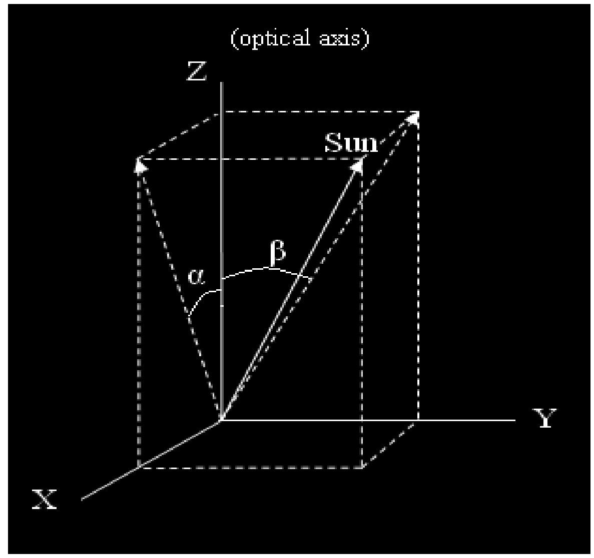


Figure 7 - Sun Vector in Sensor's Body Frame

Sun vector can accurately be determined once the values of three calibrating coefficients are known for each line sensor. Assuming that the "sun moves" in XZ plane, the relationship between the centre pixel $p_{i\alpha}$ of illuminated area of the X-line sensor and the incident angle "α" is

$$p_{i\alpha} = p_{c\alpha} + k_\alpha \times \tan(\alpha - \alpha_{OFF}) \qquad (3)$$

Where

- $p_{c\alpha}$, pixel in the centre of illuminated area if optical axis is directed to Sun
- k_α, multiplying coefficient (sensitivity to the change of angle) α, angle to Sun in XZ plane
- α_{OFF}, difference between mechanical and optical axis (non-co linearity of the line sensor with the opaque layer)

The above three are the needed calibration coefficients. Calibration co-efficients for the Y-line sensor ($p_{c\beta}$, k_β and β_{OFF}) are defined in the same manner.

$$p_{i\beta} = p_{c\beta} + k_\beta \times \tan(\beta - \beta_{OFF}) \qquad (4)$$

Practically the sun is not only in the ZX or ZY plane, as a result the distance h between the CMOS line array and effective part of the slit increases by a factor inversely related to the cosine of the angle of deviation in the other plane (see figure 1). To incorporate this effect the equations 3 and 4 are modified as,

$$p_{i\alpha} = p_{c\alpha} + \frac{k_\alpha}{\cos(\beta)} \times \tan(\alpha - \alpha_{OFF}) \qquad (5)$$

$$p_{i\beta} = p_{c\beta} + \frac{k_\beta}{\cos(\alpha)} \times \tan(\beta - \beta_{OFF}) \qquad (6)$$

These nonlinear equations can be solved by an iteration process that requires few steps. Initially assuming cosine to be unity and solving just equations 3, 4 to get an estimate of α_1, β_1. Next we use equations 5 & 6 to calculate new estimates α_2, β_2. We repeatedly perform the calculation until new estimates α_{k+1}, β_{k+1} differ from the old ones α_k, β_k by a factor less than the accuracy of the sensor.

5.1 Determining the Sun Vector

Once the two angles are determined, the unit vector in the direction of Sun $\hat{S}$ in sensors frame can simply be found by taking z component as a unit vector.

Then

$$x = \tan(\alpha) \qquad (5)$$

$$y = \tan(\beta) \qquad (6)$$

And

$$\hat{S} = \frac{[x, y, z]}{\sqrt{x^2 + y^2 + z^2}} \qquad (7)$$

5.2 Calibration

For calibration the sensor was fixed on a surface while the sun simulator placed roughly perpendicular to the DSS surface. The DSS was connected via serial interface to a PC equipped with Matlab. The values of calibrating coefficients $p_{c\alpha}$, α_{OFF}, k_α, $p_{c\beta}$, β_{OFF}, k_β were calculated.

Figure 8 shows a plot of digital values of 2048 pixels. Two frames of 1024 pixels are shown in the plot; peeks represent the illuminated pixels that are highlighted by the incident light ray.

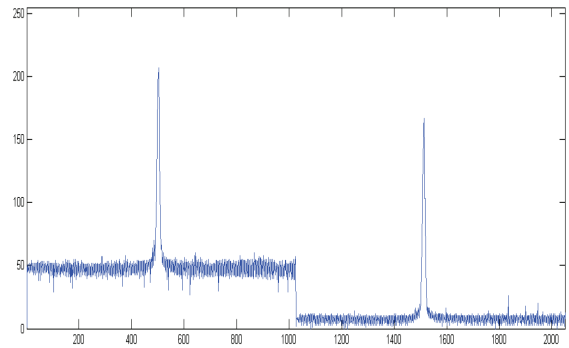


Figure 8 - Digital values of all 2048 pixels during one scan cycle

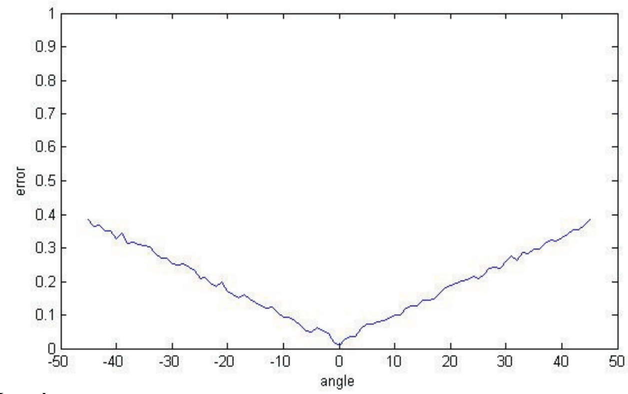


Figure 9 - Error in measured angle of α for X-line sensor

6 RESULTS

For testing, the DSS is to be placed perpendicular to the Sun Simulator, upon a test bed capable of providing a tilt angle of ±45° with a step of 1°.
First the DSS is rotated about the Y-axis, varying α between ± 45°, to determine the response of X-line sensor. To determine the response of Y-line sensor, β is varied between ± 45° by rotating sensor about X-axis. Figure 9 shows a graph between error and angle tilt provided by the test bed, where error is the difference between the provided and measured angles. The results show that the angle determination accuracy of the sensors remains well under 0.5° over entire field of view of ± 45°. The observed increase in the error as we move from the centre of the active area of line sensor towards the edges is because of the fact that light entering through the slit at a greater angle illuminates more number of pixels. The error at large angle can be decreased by introducing some sort of thresholding algorithm.

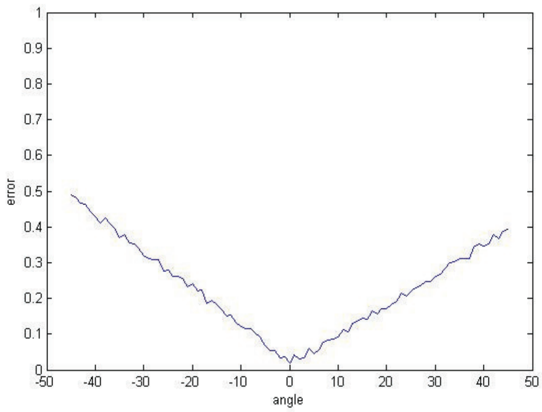


Figure 10 - Error in measured angle of β for Y-line sensor

Table 1 - Technical Specifications of the developed DSS.

1	No of pixels	1024
2	Field of view	±45^o
3	Accuracy	0.5^o
4	Size	91 x 108 x 44
5	Weight	0.4 kg
6	Output	Computed Sun Vector or 8-bit digital value of 2048 pixels
7	Baud rate	57600
8	Electrical Interface	RS232 / CAN
9	Input Power	0.25 watt
10	Supply Voltage	+5 volt

7 CONCLUSION

A simple, low cost and power efficient Digital Sun Sensor has been designed and implemented, having a Sun vector determination accuracy of 0.5^o for a field of view of ±45^o. This was the first version of the DSS. In later versions, the design can be greatly reduced in size and weight just by replacing through-hole components with the surface-mounted counterparts. The accuracy of the sensor can be improved up to 0.1 degree by enhancing the slit design.

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