DEVELOPMENT OF MINIATURE DIGITAL SUN SENSORS AT NCKU

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1. ABSTRACT

New digital sun sensors are being developed at the National Cheng Kung University (NCKU) of Tainan, Taiwan for the implementation in nano- and picosatellites. The development aims to produce highly miniaturized stand-alone sensors for the determination of the sun vector in the satellite's body frame. The sensors are designed with the objective to keep mass, size and power consumption at a minimum in order to make them especially attractive for the implementation in very small satellites. This paper describes the measurement principle of the sensors and provides insight into the hardware and software developments.

KEYWORDS：Digital Sun Sensor, Attitude Determination, Nanosatellite

2. INTRODUCTION

The growing number of small satellite developments for various mission scenarios have increased the needs for miniaturized sensor elements with high precision. In particular the ability and performance of the attitude control subsystem of a spacecraft depends heavily on the accurateness of the measurement instruments. This research therefore concentrates on the miniaturization of sun sensors, which are a commonly employed technology for attitude determination. Sun sensors are used in the majority of satellites that need to determine their attitude for attitude control purposes.

In general there are two categories of sun sensors – analog and digital types. Analog sun sensors output an analog current from which the sun angles can be derived directly (Giesselmann et al, 2003).

Digital sun sensors on the other hand illuminate sensor elements, which are located at the focal plane. Through digital processing a sun angle is then obtained. Up to now, analog sun sensors are still very popular due to their simplicity and because they are relatively cheap. However, they also have inherent limitations, such as reduced accuracy for greater sun angles. Digital sun sensors on the other hand usually provide high accuracy for a large field of view (de Boom et al, 2003).

A conventional digital sun sensor would usually consist of sensor elements placed in a certain configuration (e.g. Gray-code scheme) on the focal plane and the optical head being a slab, with certain index of refraction, on whose upper side a narrow slit allows entrance for the sun rays (Sidi, 1997).

The digital sun sensor in this paper applies a different approach. It essentially consists of an image sensor at the focal plane and a mask placed in front of it at a certain distance. The mask has a tiny pinhole etched in its center, which produces a spot light of the incident sun rays on the focus plane. A microcontroller determines the spot location within the sensor field and, given the knowledge of the sensor configuration obtained through the calibration process, outputs the sun vector coordinates.

3. MEASUREMENT PRINCIPLE

The principle of the measurement is illustrated in Figure 1. A thin mask is placed in small distance in front of an image sensor. Through the pinhole in the masks' center sun rays enter and illuminate a portion of pixels of the sensor. Depending on the tilt of the sun sensor in regards to the incident light, this sun spot is located somewhere on the sensor field as long as the sun is within the field of view of the sensor.

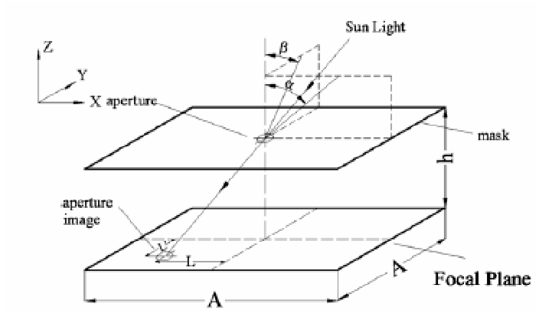

Figure 1: Measurement Principle

Once a clear image of the sun spot is captured, the location of the sun spot center is then obtained through filtering and spot detection algorithms. For this computational task a microcontroller is implemented, which also manages the command and data communication.

4. SYSTEM CONFIGURATION

The digital sun sensor is composed of four main components: the image sensor, the mask, the spacer, and the microcontroller. With the additional electronics it is assembled onto a single PCB board, which also provides mounting possibilities.

A commercially available CMOS image sensor is being used, which offers an integrated pixel buffer that allows for the absence of additional SRAM for image buffering.

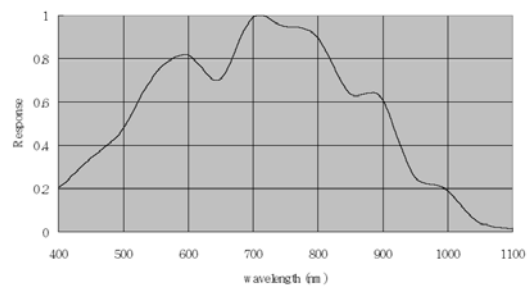

Figure 2: Spectral Response of Image Sensor

The mask is produced with a tiny hole in its center with a diameter of a few micrometers. The basis of the mask is a 0.5 mm thick glass filter. On top of it a thin but opaque layer is applied with the small opening in its center.

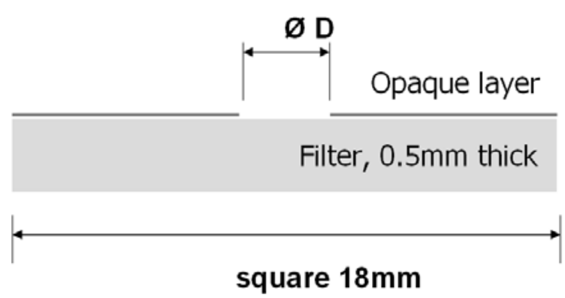

Figure 3: Section Cut of Mask

The mask cannot be mounted onto the image sensor directly because it would result in a very small field of view for the sensor. The objective of the spacer is to create a gap between the mask and the image sensor. The spacer is placed around the image sensor on the sun sensor board and allows easy insertion of the mask. The material of the spacer is Teflon in order to achieve a good thermal isolation between the sun sensor and the spacecraft structure.

A versatile 8051-based microcontroller is used for interfacing the image sensor and to provide serial communication to the external host. All electronics are mounted onto a double-sided PCB. The image sensor is placed on the front side of the PCB and all other parts are placed on the back, with a high integration density to significantly reduce its size.

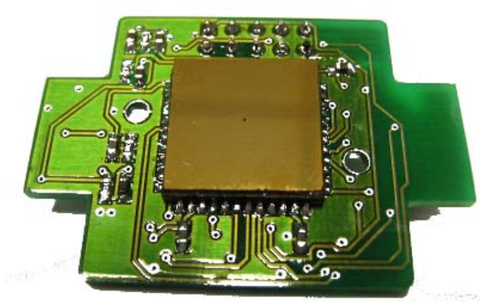

Figure 4: Prototype of the Digital Sun Sensor

5. ALGORITHMS

The measurement accuracy of the sun sensors is a function of the capability of precisely determining the center of the sun spot in the focal plane. Because the sensor is exposed to unsteady conditions – such as the fact that the light intensity on the image sensor strongly depends upon the angle of incidence for a given exposure time – the algorithms for image capturing and sun spot detection must incorporate high degree of adaptability.

The flow of operation can be summarized as follows. In the first step, an automatic exposure control procedure is executed that iteratively adjusts the exposure time until an acceptable image is captured. Then the image is passed on to the next process, which is the coarse detection of the spot center.

The coarse spot detection outputs the coordinates of the spot center. Around these coordinates a region of interest (ROI) is placed. The windowing method is used to reduce computational overhead when applying the centroiding function by focusing the attention to the region of interest (Liebe et al, 2002). With the chosen mask design and its tiny pinhole, it is assured that the sun spot always lies entirely inside the captured window. This centroiding process then yields the accurate center positions. The output of the digital sun sensor is a sun-pointing unit vector, which is calculated from the coordinates of the actual sun spot center and the coordinates of the aperture.

Automatic Exposure Control

In the ideal case the captured image would show a bright light spot in contrast with a uniformly black background. Due to the inherent system noise and because of disturbance from other light sources (such as earth Albedo, moon, and stars) this is not achievable in practice. Therefore the objective of the automatic exposure control process is to output an image that has the sun spot as the most distinctive feature. The task of this function is to adjust the image sensors' exposure time to yield a non-saturated but highly contrasted image. A controller has been implemented that, based on the measurements of saturation and total pixel energy, iteratively modulates the initial exposure time to yield the desired image. The speed of convergence to a solution is subject to optimization but even with simple control the algorithm delivers the solution after a few iterations.

Noise Reduction

CMOS technology is less susceptible to noise as compared to CCD technology. However, due to the expected high variations in temperature that the sun sensor will endure in orbit, the implementation of an effective noise filter in the software is indispensable.

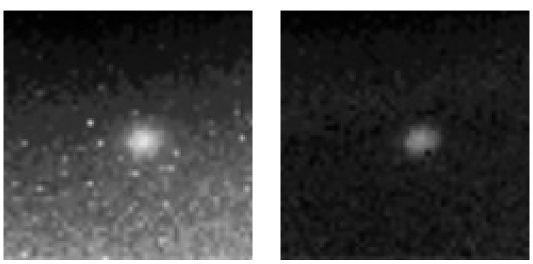

Figure 5: Noisy Image and Filtered Image

Dynamic Thresholding

Thresholding is applied to the filtered image to divide it into sunlit pixels and background. Each pixel whose value is below the threshold is erased to its reset value. At the end of the process, only those pixels remain which exceed the threshold value and hence expectantly belong to the sun spot. The thresholding is implemented is a dynamic process.

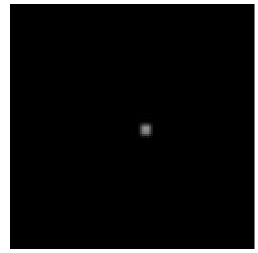

Figure 6: Thresholded Image of Sun Spot

Centroiding

Centroiding, which refers to the locating of the center of a bright spot in an image, is the fundamental process in any star tracker (Samaan, 2003). With the sun as the brightest star in our solar system it seems just naturally to apply this method for the digital sun sensor as well. The process involves some greater amount of computation, but therefore achieves greater accuracy as compared to simpler methods. The centroiding method is not applied to the entire image as this would be too time-consuming and would not yield more accurate results. Instead, a ROI is defined around the coarsely detected sun spot and the following formulas are applied:

$$x_m = \frac{\sum_{i=1}^{r}\sum_{j=1}^{s} x_{ij} I_{ij}}{\sum_{i=1}^{r}\sum_{j=1}^{s} I_{ij}} \quad y_m = \frac{\sum_{i=1}^{r}\sum_{j=1}^{s} y_{ij} I_{ij}}{\sum_{i=1}^{r}\sum_{j=1}^{s} I_{ij}} \qquad (1)$$

where:

I_{ij}	intensity value at the (i, j)th pixel
x_{ij} , y_{ij}	position of the (i, j)th pixel
r,s	dimension of ROI window

The x_m and y_m values are then added to the ROI window coordinates to yield the spot coordinates in reference to the image field origin. Using this method, the sun spot center is computed with sub-pixel accuracy.

6. CONCLUSION

The design of a miniature digital sun sensor that is under development at the National Cheng Kung University in Taiwan has been reported in this paper. The sun vector is determined as a function of the sun spot position within the focal plane of an image sensor. The assembled device is extremely small, light and consumes less then 100mW in operation. Its expected accuracy is in the sub-degree region. Due to its flexibility of illumination conditions, the sun sensors application may also be of equal interest for planetary rovers or even terrestrial applications.

7. ACKNOWLEDGMENTS

The authors would like to thankfully acknowledge the support of the National Space Program Organization of Taiwan under Grant 95-NSPO(B)-SE-FA09-01(II).

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