Design and Development of Digital CMOS Sun Sensors for Precise Attitude Determination of Small Satellites

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The Department of Astronautics and Aeronautics of the National Cheng Kung University is currently developing a miniaturized digital sun sensor for the implementation into a 2kg Nanosatellite, labeled PACESAT and a 30-kg Microsatellite, labeled LEAP. The development aims to produce a highly integrated, high accurate stand-alone sensing device for the precise determination of the actual sun vector in regards to the satellites' body-frame. With the stringent requirements in terms of mass, size and power consumption that small satellites have to deal with, the development makes use of MEMS technology and other methods for significant reduction in those areas.

The proposed digital sun sensor essentially consists of an image sensor array field, equipped with a mask placed on it. The mask has a tiny pinhole in its center, which produces a spot light of the incident sun rays on the focus plane. A microcontroller reads out the spot location and, taking the relations of the geometric properties and alignments of the sensor into account, calculates the corresponding angles of the sun for the two axes. The software integrates filter, spot detection and sun vector calculation algorithms. The main goal of the development of this sensor is to produce a high accurate measurement device at extreme miniaturization, low power consumption and low costs as compared to on-market available devices.

Measurement Principle

The principle of the measurement is illustrated in figure 1. A thin mask (fabricated with MEMS technology) is covering the top of a CMOS image sensor. Through the pinhole in the center of the mask sun rays enter and illuminate a region of pixels on the sensor. Depending on the angle of the incident light, the light spot is located somewhere on the sensor field within the field of view (FOV). The center of the illuminated region will be determined

through filtering, followed by the detection of the sun spot. A computation then yields the center of this spot on the focal plane. With this numbers and the given geometrical properties of the system assembly and by further taking into account the offsets of physical hardware alignments (determined by the calibration process) the sun angles are finally calculated.

Table 1: Sensor Specification

Sensor Type	CMOS Sensor w/ digital control unit
Mask	MEMS pinhole filter mask
FOV	± 60°
Resolution	0.5°
Software Interface	UART (TX/RX), self-defined protocol
Data Output	Alpha and Beta angles (±nn.nn[°])
Power Consumption	Active: <200mW (at 5 Volt) Idle: <3mW
Mass	20 grams

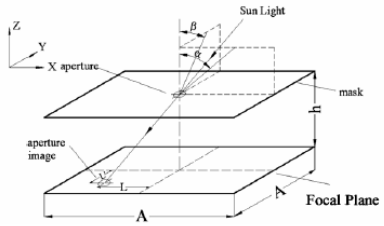

Figure 1: Measurement Principle

Main Components

As the sensing device a CMOS image sensor (ARAMIS EVS250K) from the Taiwan-based company ElecVision is used. The active pixel area is 512x492 pixels. Compared with CCD technology, CMOS offers the inherent advantage of low power consumption and further it integrates all of the additional circuitry on the chip, such as A/D converter, timing electronics, etc. This reduces the part count significantly. To achieve a high contrast image for optimal sun sensing, the exposure time of the sensing chip can be controlled and the reset voltage of the pixels can also be adjusted. The chip further provides the fairly exceptional feature of multiple and randomly read-out of single pixels. Therefore no additional memory is needed to buffer a captured image since all the processing can be done by accessing the chip’s pixel information directly.

The mask is a 500 micron layer of silicon, which is coated with chrome (100 Angstroms) and a film of gold (5000 Angstroms). The chrome is necessary since the gold layer alone would not adhere to the silicon. The gold film has a rectangular pinhole of 35µm diameter. It is positioned above the center of the pixel array. The mask is produced with MEMS fabrication technique because the MEMS lithography provides the extremely required high precision.

A versatile 8051-based microcontroller is used for image processing and computations. Further the microcontroller provides standard interface for connection to an attitude control system.

Software Algorithms

The sun rays pass the mask aperture and leave a light spot on the focal plane (the sensor field). The computation of the sun angles as a function of the spots position, involves the following steps: First, a threshold filter distinguishes between sun-lit pixels and background. Then a spot detection module delivers the center of the sun spot on the focal plane. With this coordinates the sun vector and the sun angles are calculated. All the calculation is done with the integrated microcontroller. The following sections describe the algorithms in greater detail.

The hardware filter (the silicon wafer) cuts off a large spectrum of the incident light, whereas the software filter is needed to achieve precise distinguishing between sun spot and background. Thus it is especially crucial to determine a functional value for this bi-level thresholding, in order that only sun-valid pixels remain. An optimal threshold value will be investigated in the calibration procedure.

Following the filter process, the detection of the sun spot's center is subject to computation. For the purpose of evaluation, two different approaches are being investigated: one is edge detection and the other one is centroiding. The principle of the first approach is as following: four raster lines are initialized as the borders of the sensor field. The coarse detection mode then scans the pixel array every. Once a sun spot pixel is detected, the algorithm switches into fine detection mode. A Region of Interest (ROI) window is applied with the detected pixel in the center. The ROI window has to be more than double the size of the largest possible sun spot (at the borders of the sensor field). Now this ROI is scanned pixel by pixel, line by line and searched for valid sun spot pixels. Each detected valid pixel follows a comparison of its coordinates with the positions of the actual borderlines. For example, if the detected pixel has a lower x coordinate than the right scan border then the scan border line is moved to this position. The final result is a small rectangular within the sensor field, whose geometrical center yields the coordinates of the sun spot center. The centroiding method is routinely used in star trackers. The process involves some greater amount of computation, but therefore provides also greater accuracy. Also, the first step is a line-based scanning of the sensor field.

Once a sun pixel is detected, a ROI window with its center at the detected pixel's coordinates is loaded into a buffer. In the following method, also called the moment method, the center of the sun spot is determined in analogy to the determination of the center of mass using the momentum technique. Following the filtering and the spot center detection, the final algorithm will calculate the angles as a function of the given geometrical properties of the sensor assembly, offset values and the actual sun spot location. This process is straightforward. Its accuracy is limited only by the precision of the processing unit, which is by magnitudes higher than the taken measurements. Therefore the bottleneck in this whole computation chain is the input delivered by the previous process of center detection, which therefore is aimed to be as precise as possible.

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