MICRO SUN SENSOR FOR SPACECRAFT ATTITUDE CONTROL

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Abstract: A micro sun sensor is being developed for use on a Mars rover for the Mars Science Laboratory Mission. The micro sun sensor, which is basically a small pinhole camera, consists of a small mask with pinholes, placed on top of an image detector. Images of the sun are formed on the image detector when the sun illuminates the mask. Image processing is performed in the sun sensor that outputs 4 sun centroids, which the rover's main computer converts into sun angles for high gain antenna pointing and heading determination. Copyright © 2004 IFAC

Keywords: Attitude algorithms, Cameras, Image Sensors, Navigation Systems, Microsystems.

1. INTRODUCTION

NASA proposes to develop and to launch a roving long-range, long-duration science laboratory that will be a major leap in surface measurements and pave the way for a future sample return mission. NASA is studying options to launch this mobile science laboratory mission as early as 2009. This capability will also demonstrate the technology for "smart landers" with accurate landing and hazard avoidance in order to reach what may be very promising but difficult-to-reach scientific sites.

Later this year, the type of scientific equipment loaded on MSL will be determined. It will include an analytic suite of instruments. Already selected is a core drill and crusher that delivers ground up samples for detailed, onboard study.

All Mars rovers up to date have used sun sensors to determine the sun orientation. This information is used in combination with the data from an inclinometer, a clock, and the ephemeris of the Sun Earth and Mars, to determine the rover heading, to point the high gain antenna at Earth, and to provide a reference for the inertial measurement unit that is used for rover navigation.

At the Jet Propulsion Laboratory, California Institute of Technology a novel Micro Sun Sensor (MSS) has been developed [1]-[7].

Two categories of conventional sun sensors exist - digital and analog types. The digital sun sensor illuminates different geometric patterns on the detector plane. The presence or absence of light imaged on the plane defines a digital signal that can be translated into the sun angle. In comparison, an analog sun sensor outputs analog currents, from which the sun angles can be derived directly [8]. To enhance the capabilities of these traditional sun sensor devices, a new generation of sun sensors is emerging. These sun sensors utilize an imaging device as the detector plane with a mask placed in front of it. The sun sensor determines sun angles based on the location of the image pattern on the detector plane [9]-[14].

Fundamentally, the MSS is a miniaturized pinhole camera. The focal plane is an Active Pixel Sensor (APS) camera on a chip and the optics is a small piece of silicon wafer. APS chips have the advantage over traditional CCD chips in that they are based on regular CMOS technology [15]. This means that additional circuitry such as A/D converter, timing, and communication can be integrated on the focal plane itself [16]-[17]. The APS chip that the MSS is based on has all camera functions integrated on the chip itself [18].

The optics of the miniaturized camera is a piece of silicon wafer with an evaporated layer of chrome and gold on one side with a number of small pinholes in the gold layer. The silicon wafer is mounted ~700 microns from the focal plane making the system into a pinhole camera. The Sun is so bright that it will penetrate the silicon wafer where there are apertures and the rays will form an image. This is basically the same principle as in a sundial. This is sketched in Fig. 1.

![Fig. 1. The MSS Concept](image-url)

The MSS fundamentally consists of 3 parts: 1) mask, 2) spacer and 3) focal plane. The packaged parts are shown in Fig. 2 and an exploded sketch is shown in Fig. 3. The APS chip is wire bonded to the PCB, the
spacer fitting outside the wire bonded APS chip, and the mask mounted on top of the spacer.

Fig. 2. Sketch of the packaged APS chip, spacer and mask on a PCB board

Mask Spacer

Fig. 3. An exploded view of the packaged mask and APS chip

2. MEMS MASK

To fabricate masks with closely aligned micro size pinholes, MEMS fabrication techniques are required because the MEMS lithography-technique has extremely high precision and is well controlled. The MEMS mask is shown in Fig. 4.

The MEMS mask is fabricated by depositing a thin layer of chrome and a thicker layer of gold on a double polished silicon wafer. The silicon and chrome attenuates the light and the layer of gold blocks the light except through the 21 apertures.

The reason for the asymmetric pattern of apertures is discussed in details under the sun sensor electronics section.

3. SPACER

The silicon mask cannot be mounted on the focal plane itself because of the high refractive index of silicon and reliability/vibration concerns. The objective of the spacer is therefore to separate the pinholes from the focal plane with a gap (low refractive index) of ~700 microns. The spacer is coated with gold so it is opaque to sunlight. It is sketched in Fig. 5.

Fig. 4. The MEMS pinhole mask layout

Fig. 5. Sketch of the spacer

4. APS DETECTOR

The Versatile Integrated Digital Imager (VIDI) 512 is a complete CMOS imaging system on a chip [18]. The VIDI contains a 512 x 512 imaging array, 512 A/D converters (one for each column), D/A converters that control the internal reference voltages, currents, and a digital control block. The imager configuration is programmed through the serial input port. The configuration determines the pixel timing and ADC signals that are generated internally. After the imager is configured, a single command through the serial input port will cause image data to be taken. The images are output in parallel (one pixel at a time). The imager can be programmed to perform an internal column voltage offset correction to minimize column fixed pattern noise.

A summary of the VIDI specifications is given in Table 1.

Table 1. Summary of measured parameter values for VIDI

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>CMOS, 0.5μm</td>
</tr>
<tr>
<td>Outputs</td>
<td>Analog &amp; Digital</td>
</tr>
<tr>
<td>Format</td>
<td>512 x 512</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>12 μm x 12 μm</td>
</tr>
<tr>
<td>Responsivity</td>
<td>4 μV/photon</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>3% (@ 1050 nm)</td>
</tr>
<tr>
<td>Dark Current</td>
<td>300 pA/cm²</td>
</tr>
<tr>
<td>Noise</td>
<td>40 e-</td>
</tr>
<tr>
<td>ADC resolution</td>
<td>10 bits (9.3 bits effective)</td>
</tr>
<tr>
<td>Power</td>
<td>10 mW @ 30 FPS</td>
</tr>
</tbody>
</table>
5. SUN SENSOR FUNCTIONALITY

Various degrees of data processing can be included in a sun sensor design. In one extreme case the MSS outputs the raw images (no processing of the data) and in the other extreme case the MSS can be designed to output sun angles directly (full data processing). A trade study was conducted to select an appropriate MSS functionality.

1. Output the full images

The MSS can output raw images and not do any processing. This minimizes the mass and the power consumption of the MSS, but full images (256 Kbytes) have to be outputted at each update. At 8 Hz update rate the required bandwidth is 256kBytes x 8 = 2Mbytedsec.

2. Output the position and brightness of the bright pixels

In an image of the sun, only a small fraction of the pixels contains information (the bright pixels). All dark pixels do not contain any information. An MSS could therefore be designed to only output the position and brightness of the bright pixels. Sun imaged through each of the mask apertures covers approximately 25 pixels on the detector. The position and brightness of each pixel contains 26 bits of information (2 x 9 bits for position and 8 for brightness). Each aperture, therefore, contains 650 bits of information. It is desirable to have more than one aperture for redundancy (should it be covered with contamination or dust). Assuming 4 apertures would result in 2600 bits of information at each update.

3. Output the raw pixel data in windows

Another way to split the processing burden is to only output the raw pixels in small windows around the aperture images (assuming it is known where to place the windows). An appropriate size of a window would be 8 x 8 pixels or 512 bits. Assuming 4 windows and 8 Hz update rate would result in ~2Kbytedsecond data rate.

4. Output the centroids

Another way of splitting the processing burden is to have the MSS do the centroid calculations and only output the centroid positions and the brightness. The centroid information can be contains in 32 bits (8 bits for brightness and 2 x 12 bits for positions). Assuming that 4 apertures are utilized, then the information is 16 bytes per update. At 8 Hz update rate, the sun sensor will only occupy 128 bytes/second.

5. Outputting angles

It is also possible for the sensor to calculate and output the sun angles directly. This will require very low bandwidth because the information from all apertures is combined into a single angle estimate. It is estimated that the angle information can be contained in 5 bytes per update. However, there are two complications to this approach. 1) Floating point trigonometrical operations are utilized to transform the centroids into angles. This will have to implemented in hardware and 2) the calibration is performed after the final assembly and the calibration constants would have to be downloaded into an EEPROM.

The different functionalities and required bandwidths are summarized in Table 2.

Table 2: Different functionality and bandwidth requirements

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Bandwidth</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw images</td>
<td>2 Mbytes/sec</td>
<td>Low</td>
</tr>
<tr>
<td>Bright Pixels</td>
<td>2.6 Kbytes/sec</td>
<td>Medium</td>
</tr>
<tr>
<td>Windows</td>
<td>2.0 Kbytes/sec</td>
<td>Medium</td>
</tr>
<tr>
<td>Centroids</td>
<td>128 bytes/sec</td>
<td>High</td>
</tr>
<tr>
<td>Angles</td>
<td>40 bytes/sec</td>
<td>Very High</td>
</tr>
</tbody>
</table>

Among all options considered only two (4 & 5) meet the MSL bandwidth requirements. Due to much lower hardware requirements, option 4 was selected for implementation.

6. SUN SENSOR ELECTRONICS

It was decided to implement the processing in a single FPGA to minimize mass and power consumption. A high level electronic block diagram is shown in Fig. 6.

Fig. 6. Block diagram of the MSS Electronics

The amount of logic that can be fitted in a single radiation tolerant FPGA is limited (~50,000 gates). Also, the lack of memory requires that all processing be done on the fly. Therefore, many design choices were driven by the desire to simplify the complexity.

In Fig. 7, the 21 apertures are observed, however 3 hot pixels are also observed (smaller dots). Hot pixels are pixels with a defect that makes it look like they are illuminated when they are not. This phenomenon is typically observed when an APS chip has accumulated some radiation dose.
Fig. 7. Sketch of a sun image

The FPGA will scan all pixels in the image starting in the upper left corner scanning one row at a time. The FPGA will ignore bright pixels that are isolated (i.e. the brightness difference to its right and left neighbor pixel is larger than a threshold). This is the hot pixel filter. The first time that the FPGA encounters a bright pixel (over a given threshold) the FPGA chip will stop and place 4 large windows on 32 x 32 pixels in a fixed position relative to first detected bright pixel (upper left corner of the first window is 80 pixels down and 12 pixel to the left). This is sketched in Fig. 8. The first encountered bright pixel is marked with a + and the 4 windows are marked with gray boxes.

Fig. 8. Sketch of the first bright pixel found by the FPGA and placing of the 4 windows

As the FPGA reads more pixel data, each time it encounters a pixel that is inside one of the 4 boxes and above a threshold, it will add the product of the x counter and the pixel value (minus threshold) to a register, the product of the y counter and the pixel value (minus threshold) to another register and the pixel value (minus threshold) to a third register. Once the entire image has been read out, the x sums, y sums and the pixel brightness sum for all 4 windows are read out to the rover/spacecraft. The numbers are not divided to minimize the complexity of the FPGA design.

The mask is specially designed to cope with a situation where one or more apertures are blocked (e.g. Mars dust). Fig. 9 is a sketch of a case where 3 apertures have been disabled including the reference aperture that the FPGA encountered as the first bright pixel in Fig. 8. Also, the whole aperture pattern has moved to a new location due to a different sun angle.

Fig. 9. Sketch of a sun image with 3 apertures blocked

The FPGA will now identify a different pixel as the first bright pixel and will place the 4 windows accordingly. The situation is sketched in Fig. 10.

Fig. 10. Sketch of the reference aperture and the windows placed on bright pixels

In this case the FPGA will still output 4 centroids, where number 3 has a brightness that is close to zero because the aperture is disabled. Also, the 4 apertures are not the same apertures as in the normal case. Since the sun angle is unknown, how can the spacecraft/rover determine what set of apertures that the sun sensor is outputting? This can be determined because the distance between centroid 1 and centroid
2 is ~37 pixels in the first row, ~32 pixels in the second row and ~27 pixels in the third row. Similar distance apriori knowledge exists about the other apertures.

The reason that the mask have 6 apertures when only 4 are being used is that the sun sensor also has a imaging mode, where it is possible to read out an entire image over several exposures. This mode can also be used during flight for very high accuracy sun angles determination but the update time will be many seconds.

7. ALGORITHMS

When the rover receives the x sums, y sums and brightness sums for each aperture, it divides the x and y sums with the brightness sum to avoid that the FPGA has to do the division. Based on the distances between the centroids, it is also able to identify which centroids it used.

The next step in the algorithmic flow is to transform the (x,y) centroids into sun angles. A simple pinhole camera model is used. The pinhole camera model includes the distance from the pinhole to the focal plane (F) and the intersection of the optical axis and the focal plane (x₀,y₀). It is possible to transform from centroid coordinates into a unit vector centered at the pinhole and pointing towards the Sun utilizing the following equation [19]:

\[
\begin{bmatrix}
  i \\
  j \\
  k \\
\end{bmatrix} = \begin{bmatrix}
  \cos(\text{atan2}(x-x_0, y-y_0)) - \cos(\frac{\pi}{2} - \text{atan2}(\frac{x-x_0}{F} + \frac{y-y_0}{F})) \\
  \sin(\text{atan2}(x-x_0, y-y_0)) - \cos(\frac{\pi}{2} - \text{atan2}(\frac{x-x_0}{F} + \frac{y-y_0}{F})) \\
  \sin(\frac{\pi}{2} - \text{atan2}(\frac{x-x_0}{F} + \frac{y-y_0}{F})) \\
\end{bmatrix}
\]

Where atan2 is four-quadrant inverse tangent and \((i,j,k)\) is the unit vector starting at the pinhole and pointing towards the Sun. The camera pinhole model is sketched in Fig. 11. The rover or flight computer has a set of calibration parameters for each aperture.

The accuracy of the sun sensor depends on over how large a field of view that it is calibrated to operate. A single aperture from a MSS prototype was calibrated over different FOVs. The accuracy is estimated as the average calibration residual. The result is shown in Fig. 12.

4 different unit vectors pointing towards the sun is calculated (one for each pinhole). The next step is to "average" these 4 vectors. A theory for calculating "average vectors" is given in [20]. Assuming that the 4 pinholes are independent, then the accuracy of the average vector towards the Sun will be improved by a factor of \(\sqrt{4}=2\) relative to the accuracy of a single aperture.
8. SUMMARY

A new type of sun sensor is being developed for the Mars Science Laboratory mission.

A tiny gold and chrome plated silicon wafer is bonded on top of a spacer that is bonded to the PCB over the APS chip that is mounted with chip onboard technology. The APS chip contains all camera functions on the chip. The mask consists of 21 pinholes, but the MSS typically only outputs 4 centroids. The sun angle can be determined based on the position of the aperture centroids – just like a sundial.

Projected specifications for the MSS are shown in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>&lt;35 grams</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;300 mW</td>
</tr>
<tr>
<td>Accuracy</td>
<td>&lt;0.2° when sun is &lt;20° from the boresight, &lt;0.5° when the sun is &gt;20° from the boresight</td>
</tr>
<tr>
<td>Update rate</td>
<td>2 Hz</td>
</tr>
<tr>
<td>Interface</td>
<td>UART</td>
</tr>
<tr>
<td>Field of view</td>
<td>+/- 60°</td>
</tr>
<tr>
<td>Slew rate</td>
<td>&gt;12°/sec</td>
</tr>
</tbody>
</table>

ACKNOWLEDGEMENTS

The authors would like to thank Nan Katanyoutanant and James Naegle for discussions about the FPGA chip.

The research described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. References herein to any specific commercial product, process or service by trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES