AN OPTICAL LINE OF SIGHT SENSOR FOR THE PINHOLE FACILITY

Michael Greene and Hong Tan

Department of Electrical Engineering
Auburn University, AL 36849

ABSTRACT

A scale model of the optical line of sight sensor which measures the pointing angle error to the sun for the Pinhole Facility has been designed and tested in the laboratory. This sensor consists of a pinhole camera with two pairs of perpendicularly mounted linear photodiode arrays to detect the intensity distribution of the solar image produced by the pinhole. The video signal of the arrays is digitized and transferred into a microcomputer. The deflection of the image center which expresses the pointing error is calculated from these data. The experimental results show that the sensor can estimate the pointing error of 0.0167 arc seconds resolution and 0.0032 arc seconds RMS accuracy for the full scale system when the pinhole is 32 meters from the detector.

INTRODUCTION

The space shuttle based Pinhole Occulter Facility (POF) is being designed for the measurement of hard X-ray and corograph images of the sun. POF will utilize a thirty-two-meter flexible boom for separating a mask which contains X-ray pinholes and corograph shields from the detectors located in the shuttle bay. POF is shown in Figure 1.

The mask must be pointed at the sun and the detectors aligned with the mask with a high degree of pointing accuracy and stability. Failure to do so will result in smearing of the images and a loss of resolution. The disturbances that influence the pointing accuracy and stability are the shuttle thruster firing for orbit correction, motion induced by other systems, man motions on the shuttle, and gravity gradient torques.[1,2]

The line of sight sensor (LOS) monitors the position of the mask relative to the sun center and drives a three axis gimbal system to achieve pointing of the facility. This LOS consists of a basic pinhole camera with a 5 mm pinhole built in to the facility's mask. Photodiode arrays are placed along perpendicular axes on the gimbal base plate 32 meters away. Figure 2 is a drawing of the line of sight sensor. Arrays measure the outer edge of the solar image and output video format data. These data are digitized and processed via a microcomputer, where the deflection of the solar image is obtained and transformed into the mask's deflection.

NUMERICAL METHODS

The line of sight sensor measures the instantaneous deflection of the mask. This
the solar image. $AA'$ and $BB'$ can be expressed mathematically as

$$I_L = ax + b_L$$

and

$$I_R = -ax + b_R$$

respectively, where $I$ is the intensity coordinate and $x$ is position coordinate.

During the calibration of the sensor, the intensity distributions of two different known image positions are measured. In Figure 3, the center to center distance of these two images is $(x_{c2} - x_{c1})$. Since points $(x_{L1}, I_{L1})$ and $(x_{R1}, I_{R1})$ are known, the center coordinate for one axis can be calculated by

$$x_c = \frac{b_{R1} - b_{L1}}{2a} = \frac{I_{R1} - I_{L1}}{2a} + \frac{x_{L1} + x_{R1}}{2} \quad (3)$$

The intensity distributions are measured by the photodiode arrays. The output of the arrays is a series of video data pulses, each data pulse corresponding to a pixel of the array. Pixel nonuniformity and noise cause errors in determination of $(x_{L1}, I_{L1})$ and $(x_{R1}, I_{R1})$. 12 data pulses are measured for each side after a set threshold. This procedure is repeated 100 times to form a low pass filter. Averages of the 1st to the 12th data points are performed. Since the 1st pixel of 12 data points can change time to time due to noise and the averaging technique ignored this effect, errors are induced.

A modification of (3) was used to calculate the center coordinate in this experiment to correct for induced errors. It is:

$$x_{c1} = \frac{b_{R1} - b_{L1}}{2a} \times f$$

$$= \left(\frac{I_{R1} - I_{L1}}{2a} + \frac{x_{L1} + x_{R1}}{2}\right) \times f \quad (4)$$
where $a$ is the artificial slope instead of $a$, and $f$ is the correcting factor.

Similar to the calculation of $x_{c1}$, $x_{c2}$ is obtained via:

$$x_{c2} = \frac{b_{R2} - b_{L2}}{2a} \times f$$

$$= \frac{I_{k2} - I_{L2} + x_{L2} + x_{k2}}{2a} \times f$$

(5)

The artificial slope, $a$, which gives the best resolution in the image center coordinates, is about half of the real slope of the intensity distribution. When $a$ is known, the correcting factor, $f$, can be derived from the equation (6) and (7). To determine any image position, the equation

$$x_c = \frac{I_k - I_L + x_L + x_k}{2a} \times f$$

(6)

is applied, where $I_L$ and $I_k$ are the averages of 12 data points for left and right side respectively, and $x_L$ and $x_k$ are the positions corresponding to $I_L$ and $I_k$.

**EXPERIMENTAL METHODS**

Figure 4 is the block diagram of the LOS hardware configuration. The arrays output the video pulse train in a preset scanning rate. Each pulse represents the light intensity received by the corresponding pixel. A start pulse must be sent before every scan of the array. This start pulse is also used as a reset of the circuits. When the video output reaches a preset threshold, 12 data pulses are sampled using the S/H circuits. Timing is controlled by the Sample and Hold controller. After 12 data have been held, a data ready pulse triggers the microcomputer to start the "Data Selector" which sends data to A/D converter. Position of the first pixel sampled is determined by counting clock pulses until the video signal reaches the threshold. The readout of the counter is then the pixel number of the first of 12 data. The counter is reset at the start of each array scan.

Calibration has been performed in one axis. Figure 5 is the laboratory setup of the experiment, mounted on a Modern Optics air optics table. A mask with 20 cm diameter cut-off and a 200 watt lamp construct the light source. Two EG&G Reticon RCO300 256X1 photodiode arrays are mounted on the stage of minimum displacement resolution of 5 $\mu$m. The center distance between two pixels of the arrays is 25 $\mu$m. Because of the limitation of the laboratory facilities' sizes, two pinholes, instead of one 5 mm pinhole, are fixed on a stage to form the same outer edge intensity functions for left and right sides as that of the real case.

An IBM PC with Model AIO8 I/O card (Industrial Computer Source) performed sampling. ICS's AIO8 is an 8 channel 12 bit high speed A/D converter with a timer/counter board. It has 4 bits digital output and 3 bits digital input. One of the 4 AIO8 counters is used as the "pixel
number counter".

To test the sensor, the stage on which the arrays are mounted was displaced from a reference position. The displacements of the stage are equivalent to that of the image. The displacements were made step by step with the resolution of 5 µm and also were estimated by the sensor.

RESULTS

Figure 6(a) shows experimental mean estimation of the deflection vs. the ideal deflection. Figure 6(b) and 6(c) are the estimation mean error and standard deviation. The resolution and RMS accuracy of the line of sight sensor are obtained as 2.5 µm and 0.5 µm respectively which translate to 0.016 arc seconds and 0.0032 arc seconds respectively in a full scale POF system.

The accuracy of testing was limited by the experimental setup and environmental noises. The mean errors fall within the experimental limits of motion control of the stage. The standard deviations of the data reflect the noise in the building more than sensor noise. The environmental noises include the building vibration, air flows in the lab room, and many other unavoidable motions.

Another source of error is uneven slopes for the left and right intensity distribution. When
\[ a_L = - a_R = a, \]
then from equation (6)

\[ x_{\text{ideal}} = \frac{I_R - I_L}{2a} + \frac{x_L + x_R}{2} \times \phi. \]

where \( a_L \) and \( a_R \) denote the left slope and right slope respectively. If \( a_L = a + \Delta a_L \) and \( a_R = a + \Delta a_R \), where \( \Delta a_L \) and \( \Delta a_R \) are small changes in slopes, then

\[ x_{\text{practical}} = \frac{I_R - I_L}{2a + (\Delta a_L - \Delta a_R)} \]

\[ = \frac{a (x_L + x_R) + \Delta a_L x_L - \Delta a_R x_R + \frac{2a}{2a + (\Delta a_L - \Delta a_R)}}{2a + (\Delta a_L - \Delta a_R)} \times \phi. \]

The error now can be calculated as (8) - (7):

\[ \Delta x_e = \frac{(I_R - I_L)(\Delta a_R - \Delta a_L)}{2a (2a + (\Delta a_L - \Delta a_R))}. \]
The uneven slope problem could be caused by the unprecise pinhole and array alignment, sun plague, and the mask deflection in two directions which results a slight distortion of the image. Suppose \( a \) to be off ideal value by \( \pm 10\% \), the magnitude of the error \( \Delta x_e \) from (9) is less than 0.4\(\mu m \) with the \( a \) and \( f \) used. The more detailed study of this error source is being started in the laboratory.

CONCLUSIONS

A laboratory model of a LOS has been developed and tested. The hardware is relatively efficient and simple. The test demonstrated that the sensor is able to provide a resolution of 2.5 \(\mu m \) with the RMS accuracy 0.5 \(\mu m \) in the measurement of pointing deflection. The results are limited by the environmental noises and the experimental setup. A new algorithm is being designed which calculates the centroid of the raw data to enables a simpler and reliable determination of image center and further studies on possible error sources are being investigated.

REFERENCES