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HIGH ACCURACY OPTICAL RATE SENSOR

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ABSTRACT

Optical rate sensors, in particular CCD arrays, will be used on Space Station Freedom to track stars in order to provide inertial attitude reference. An algorithm to provide attitude rate information by directly manipulating the sensor pixel intensity output is presented. The star image produced by a sensor in the laboratory is modeled. Simulated, moving star images are generated, and the algorithm is applied to this data for a star moving at a constant rate. The algorithm produces accurate derived rate for the above data. A step rate change requires two frames for the output of the algorithm to accurately reflect the new rate. When zero mean Gaussian noise with a standard deviation of 5 is added to the simulated data of a star image moving at a constant rate, the algorithm derives the rate with an error of 1.9 per cent at a rate of 1.28 pixels per frame.

INTRODUCTION

Optical rate sensors will be of great use on Space Station Freedom as part of the onboard guidance, navigation, and control system. These sensors can be used to track stars to provide inertial attitude reference. The information may also be used by astronomical experiments to allow reference to a known star catalog to provide precise pointing of instruments. Optical sensors can be used on Freedom to keep track of other nearby objects such as incoming orbiters. Co-orbitting platforms may also use optical sensors for their GN&C needs.

Because optical sensors will provide attitude information to Space Station, it would be useful to derive attitude rate could from these sensors. An optical rate sensor is currently being developed in the Navigation, Control, and Aeronautics Division at Johnson Space Center. The sensor will look at stars to obtain both attitude information and to derive attitude rate. A Videk Megapixel camera is supported by a Compaq Deskpro 386 for data capture and processing. The Videk camera uses a Kodak charge coupled device (CCD) array. This array is made up of 1320 horizontal by 1035 vertical pixels. The pixels are 6.8 microns square and the array is full fill. The camera is capable of 7 still frames per second; it has a grey scale of 256 levels.

In previous work on the rate sensor [1,2], two different approaches were taken. The first approach was to differentiate the centroid of the star image to obtain derived rate. A discrete-time, nonrecursive, filtering algorithm was used. The Space Station accuracy and bandwidth requirements could not simultaneously be met using this technique. The second approach was to directly manipulate the image sensor data to obtain derived rate. This technique was successfully simulated for a highly idealized star image in the presence of additive Gaussian noise.

Source stars were simulated in the laboratory by a fiber-optic strand illuminated by a light source. This laboratory setup is shown in Figure 1. The fiber-optic strand is mounted in a metal plate for stability. A filter plate with various apertures and colored filters is placed in front of the fiber optic. This assembly is attached to a micrometer drive to allow precise control of the movement of the optical fiber. The simulated star light was then passed through a collimator to make the light appear to emanate from a point source at infinity. After the light passes through the collimator, it reaches the camera.

The camera data is captured using a frame grabber.

STAR IMAGE MODELING

A three dimensional plot of a star image obtained from the above laboratory experiment is shown in Figure 2. The integration time, that is the time for which the camera shutter was open and the array was exposed to the star light, was 100 milliseconds. The data was captured for an array of 68 pixels in the x-direction by 32 pixels in the y-direction. The plot presented is actually for three frames of the same star image averaged for noise reduction.

The problem was first reduced from a two-dimensional problem to a one-dimensional problem. Column sums were performed on the array to produce the x-direction pixel sums, and row sums were performed to produce the y-direction pixel sums. This gave a one-dimensional image which was fit by a Gaussian curve of the form;

$$I(x) = be^{-(x-\mu)^2/2\sigma^2}$$

The original star image was thresholded to remove noise generated in the unilluminated pixels. All pixels with intensities less than or equal to 3.0 had their intensities set equal to zero for the thresholded star. This produced an image in which all pixels with non-zero intensity were contiguous. The center of mass and moment of inertia of the x-direction column sums were found for the thresholded star image as follows:

$$\mu = 31.1 \text{ pixels}$$
$$\sigma = 3.03 \text{ pixels}$$

Figure 3 shows a plot of the x-direction pixel sums versus a generated Gaussian with the same and , and with a peak intensity of 1,1533.

In general, a moving star image can be simulated by generating a set of Gaussian curves in which the center of mass of the image changes as a function of time. The equation for the intensity seen by a given pixel at a position x, and time, t is given below:

$$I(x,t) = be^{-(x-\mu(t))^2/2\sigma^2}$$

A set of Gaussian curves was generated for a star image with a constant rate of motion in the x-direction. A Gaussian with a peak intensity of 1200, and moment of inertia of 2.5 pixels was used to attempt to fit the central portion of the thresholded x-direction column sums. A rate of 1.28 pixels per frame for 30 frames was used for the generated images to simulate data obtained in the laboratory.

RATE SENSOR ALGORITHM

Derivation of Algorithm

Centroiding a star image to derive rate is essentially a curve-fitting problem in which the peak intensity and spread (moment of inertia) of the image are unknown. Stars of different magnitudes will have different peak intensities for the same integration time. If different integration times are used for the same star, the spread of the image may change. Knowledge of the Gaussian function, and the type of rate to be sensed is exploited to eliminate the need to determine the above parameters directly.

The algorithm is derived for the one-dimensional case, and is then extended to two-dimensions. It is important to remember that the star data to be processed is discrete in time, space, and amplitude. The algorithm is first derived by assuming the rate is constant. This implies that the position of the center of mass is the product of the rate in pixels per frame times the frame number plus an offset to account for the original position at the first frame. That is

$$\mu(f) = rf + \mu_0$$

If the offset is made zero, the intensity for a given pixel, n, at a given frame, f, for the constant rate is shown below:

$$I(n,f) = be^{-(n-rf)^2/2\sigma^2}$$

Taking the ratio of the intensity for a given pixel, n, for two successive frames gives

$$\left[\frac{I(n,f+1)}{I(n,f)}\right] = \frac{be^{-(n-r(f+1))^2/2\sigma^2}}{be^{-(n-rf)^2/2\sigma^2}}$$

$$= e^{-(r^2+2r^2f-2nr)/2\sigma^2}$$

The natural logarithm of the ratio yields

$$\ln\left[\frac{I(n,f+1)}{I(n,f)}\right] = (2nr - r^2(2f+1))/2\sigma^2$$

This is a linear function of f with slope proportional to r^2 and σ^2.

Similarly, the natural logarithm of the intensities for a given frame, f, for two adjacent pixels is given by

$$\ln\left[\frac{I(n+1,f)}{I(n,f)}\right] = -(2n + 1 - 2rf)/2\sigma^2$$

This is also a linear function of f with slope proportional to r and σ^2.

Taking the negative of the slope found previously, and dividing by the slope found above, yields the rate, r. The logarithm of the ratio is equivalent to subtracting the logarithms of the intensities. It should be noted that the peak intensity, b, and the spread of the image, σ, need never be found.

Rate Algorithm

1) Find the natural logarithms of the pixel intensities
2) Find the frame to frame differences of the log intensities for a given pixel; do this for several pixels and pairs of frames.
3) Find the frame to frame differences of the above; let the result of these

manipulations be represented by the constant, $K_f = -r^2/\sigma^2$.

4) Find the pixel to pixel differences of the log intensities for a given frame; do this for several frames and pairs of pixels.
5) Find the frame to frame differences of the above; let the result of these manipulations be represented by the constant, $K_p = r/\sigma^2$.
6) Divide $-K_f$ from 3) by K_p from 5) to obtain the rate.

RESULTS

Constant Rate Without Noise

The algorithm was applied to the simulated moving star data previously described which had a rate of 1.28 pixels per frame for 30 frames. The resulting derived values are as follows:

K_f = -0.2621;

K_p = 0.02048;

$r_{derived}$ = 1.2800; (carried out to machine precision)

Step Rate Change Without Noise

Fifteen frames of data were simulated as before with a rate r_1=1.2800 pixels per frame. At the sixteenth frame, the rate was increased by ten per cent to r_2=1.4080. Fifteen additional frame were generated at the new rate for a total of 30 frames. The constant K_f settled to its new value by the eighteenth frame; the constant K_p settled to its new value by the seventeenth frame. The correct new rate could, therefore, be derived by the eighteenth frame. Frames 16 and 17 produced outputs which could not be used to correctly derive the rate. This region of indeterminacy will be dealt with in the same way as noisy images. This method will be described in the next section.

Constant Rate Change With Noise

The algorithm was tested in the presence of noise. Gaussian noise with zero mean and standard deviation of 5 was generated. The absolute value of the noise was added to the 30 frames of generated star images moving at a constant rate of 1.2800 pixels per frame. Figure 4 shows a log plot of the generated data. As seen from Figure 4, the low intensity values were significantly distorted by the noise. Thresholding was performed on the data; all log intensities less than 4.5 were replaced with 0. The first five steps of the algorithm were performed on the noisy, thresholded data. Figure 5 shows a plot of the output of the algorithm at step 3. The spikes and numerous zero values which occur are artifacts of the thresholding. The desired data is the horizontal line just below the zero line. This data needs to be extracted from the output. A similar plot is seen for the output of step 5.

A histogramming technique similar to that employed in previous work was applied to this data [2]. Histograms of the frame differences and of the pixel differences were made. The peak frequency of zero was excluded because this is an artifact of the thresholding. Taking the second highest peak frequencies, the following values are obtained:

$$K_f = -0.2531;$$
$$K_p = 0.1940;$$
$$r_{derived} = 1.3044;$$

This represents an error of 1.9 per cent in the derived rate.

Improvements in this error performance might be obtained by increased thresholding, preprocessing to reduce the noise in the image and more sophisticated histogramming techniques. It should also be noted that histogramming techniques will handle a step rate change; the false rates obtained during the transition phase will have a low probability of occurrence, and will therefore not be included in the rate calculations. The rate is constantly updated by removing stale estimates as fresh data points are added to the histogram.

Laboratory Data

Figure 6 shows the total intensity versus the column sums for the x-direction pixels. This is 30 frames of data for a star moving at approximately four thirds of a pixel per frame. It can be seen from this plot that there are noticeable dips in the intensity at regularly spaced intervals of 16 pixels. This phenomenon was noticed toward the end of the summer program. An explanation of it was not obtained in time to compensate fully for the effect in applying the algorithm. It may be stated that, for this corrupted data, an approximation to the rate may be obtained from applying the algorithm, but the results are inaccurate at this point. The sixteen pixel periodicity in the sensor response is related to the physical process used to manufacture the CCD array.

CONCLUSIONS

The rate algorithm described works well for simulated data for the optical rate sensor. The open issues which will be addressed immediately are those of refining the model of the star image which the sensor produces, and compensating for the systematic intensity errors introduced by the CCD array. A parametric study of the algorithm, in conjunction with real sensors, needs to be performed in order to determine such quantities as allowable noise, frame rate, pixel size, number of grey levels, number of pixels and frames to be processed at one time, etc.

The algorithm is easily extended to two-dimensions by taking both the x-direction column sums to obtain the x-direction rate, and the y-direction row sums to obtain the y-direction rate in field coordinates, the field coordinates can then be transformed to the body coordinates of the vehicle.

REFERENCES

[1] Uhde-Lacovara, J., "Analysis of the Continuous Stellar Tracking Attitude Reference (CSTAR) Attitude Rate Processor", NASA/ASEE Summer Faculty Fellowship Program, 1986, Volume 2 (N87-25884 19-85).

[2] Uhde-Lacovara, J., "Optical Rate Sensor Algorithms", NASA/ASEE Summer Faculty Fellowship Program, 1989, Volume 2 (N90-24985 18-80).

FIGURE 1

Rate Sensor Optical Bench

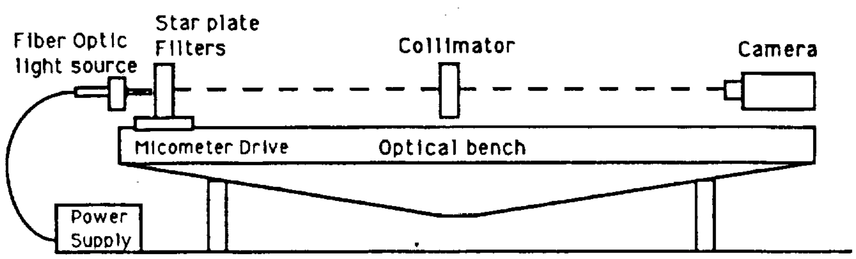

FIGURE 2

STAR IMAGE: 100 msec integration time

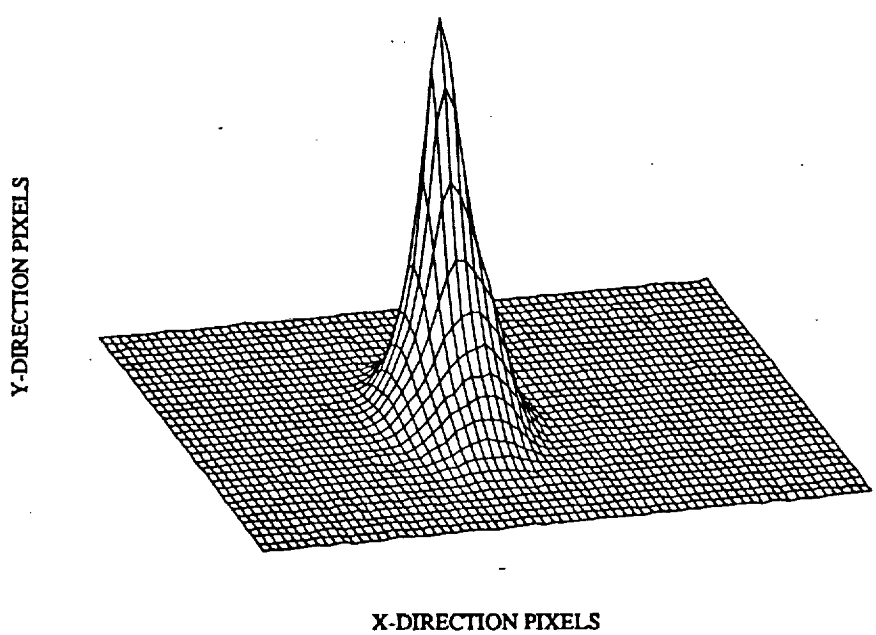

FIGURE 3

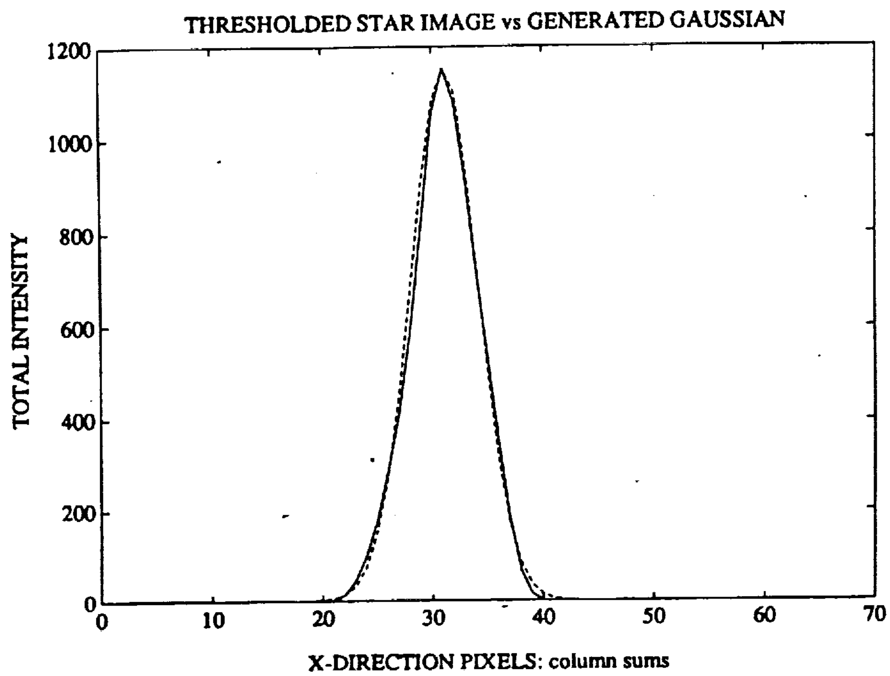

FIGURE 4

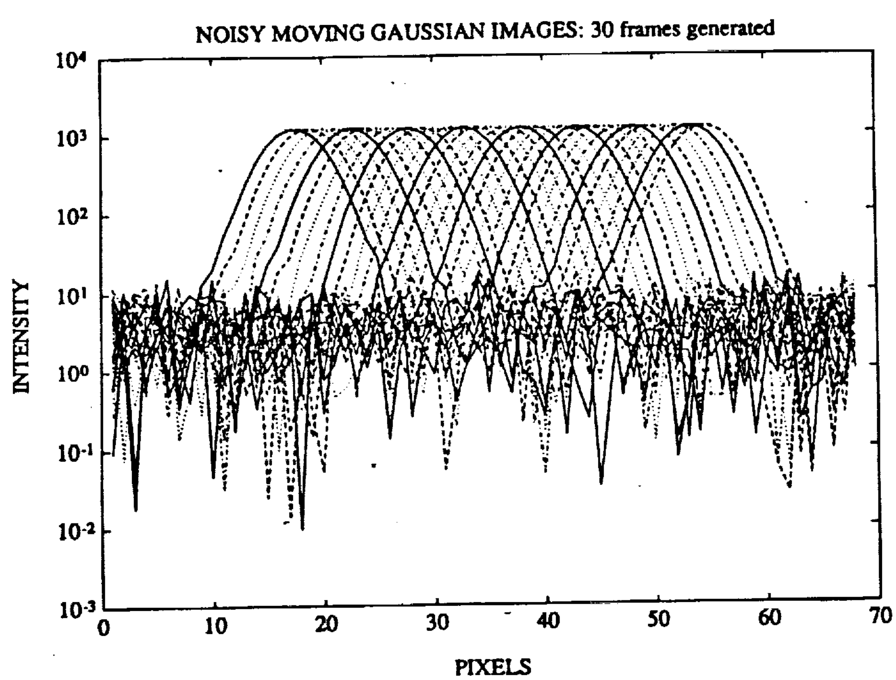

FIGURE 5

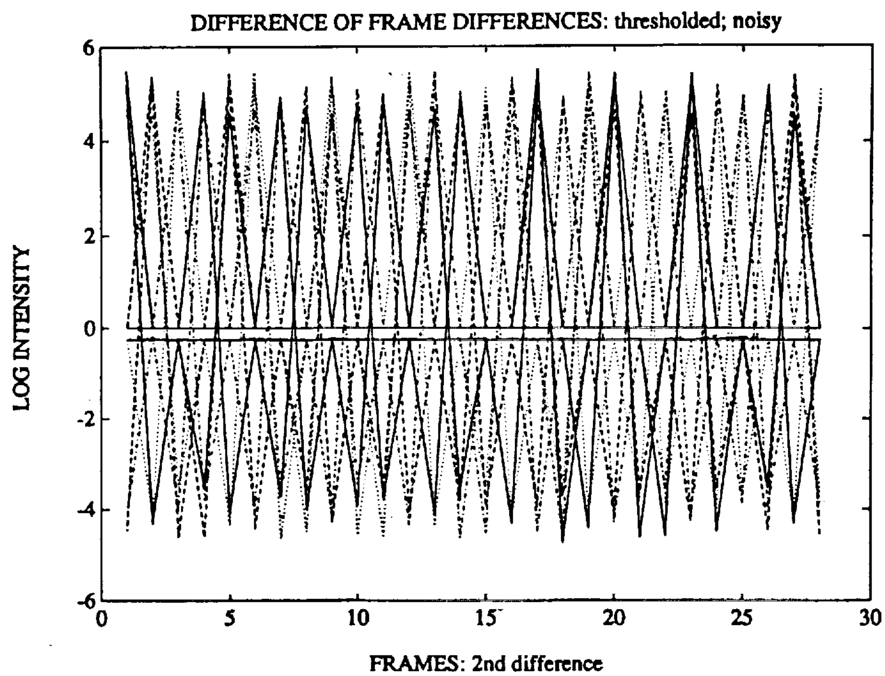

FIGURE 6