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The Spacecraft Control Laboratory Experiment Optical Attitude Measurement System

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Abstract

A stereo camera tracking system has been developed to provide a near real-time measure of the position and attitude of the Spacecraft COntrol Laboratory Experiment (SCOLE). The SCOLE is a mockup of a shuttle-like vehicle with an attached flexible mast and (simulated) antenna, and has been designed to provide a laboratory environment for the verification and testing of control laws for large flexible spacecraft. Actuators and sensors located on the shuttle and antenna sense the states of the craft and allow the position and attitude to be controlled. The stereo camera tracking system which has been developed consists of two position-sensitive detector cameras which sense the locations of small infrared light emitting diodes (LED's) attached to the surface of the shuttle. Information on shuttle position and attitude is provided in six degrees of freedom. The design of this optical system, calibration procedures, and tracking algorithm are described. The performance of the system is evaluated for yaw only.

Introduction

The Spacecraft COntrol Laboratory Experiment (SCOLE) has been designed and built to provide a test environment for the evaluation of control techniques for large flexible spacecraft (ref. 1). Specifically, the SCOLE has been developed to study slewing maneuvers and pointing operations. The principal structure consists of a lightweight (simulated) antenna attached to a shuttle-like vehicle by a long flexible mast (fig. 1). An overhead steel cable, attached to a three-axis gimbal at the shuttle base, supports the weight of the structure and allows the vehicle to move freely in pitch, roll, and yaw. In order to control the attitude of the shuttle in three degrees of freedom, as required to demonstrate slewing and pointing, sensors are required which can measure the pitch, roll, and yaw attitude of the vehicle. Previously, pitch and roll were derived from accelerometers located on the shuttle platform. An optical sensing system located external to the main structure has

recently been developed to measure the pitch, roll, and yaw angles of the SCOLE platform, as well as the x , y , and z positions of the center-of-rotation of the platform.

In the evolution of the SCOLE, a variety of sensing techniques have been considered to measure the platform attitude, specifically yaw, which could not be determined from available sensors. Examples of some of these sensing techniques include a tone modulated ultrasonic sensor, with the receiver located externally, and the transmitter located internally (on the shuttle), a star tracker, a Kalman filter estimator to derive attitude information from accelerometer and rate sensor data, and a stereo optical tracking system. Of these techniques, the stereo optical sensor system represents the best compromise between accuracy, complexity, and speed. This paper describes the sensor system, calibration procedures, tracking algorithm, and performance of this optical system.

Electro-Optical Sensing System

In the SCOLE electro-optical attitude measurement system, two position-sensitive detector (PSD) cameras are used to sense the locations of six small light emitting diodes (LED's) affixed to the surface of the shuttle (fig. 2). The cameras are interfaced to a 386 PC, which processes the information and computes the rigid body position and attitude of the shuttle in six degrees of freedom. The position and attitude information is supplied to the SCOLE computer, an MC68020-based microcomputer system.

The basic sensor used in the optical tracking system is a United Detector Technologies (UDT) planar photodiode. This 1 cm \times 1 cm silicon photodiode (a lateral effect photodiode) has four electrodes, one on each edge (ref. 2). When a photon strikes the surface of the diode, a current is generated in each electrode which is proportional to the distance between the point at which the photon struck and the corresponding edge. The location of the centroid of light falling on the detector is determined by taking the difference of the edge signals and normalizing

$$x = (x_1 - x_2) / (x_1 + x_2) \quad (1)$$

$$y = (y_1 - y_2) / (y_1 + y_2), \quad (2)$$

where x_1 , x_2 , y_1 , and y_2 are voltage outputs corresponding to the left, right, top, and bottom electrodes, respectively. To eliminate the contribution from background (room) light, an infrared filter is used which passes wavelengths longer than 880 nm.

Circuit diagrams of the camera electronics and computer interface are shown in figure 3. The output of each electrode is converted to a voltage, filtered, amplified, and digitized. The digitized signals from the four electrodes are sent over a parallel interface to a 386 PC. The (centroid) location of the light is then calculated using equations 1 and 2.

A 25 mm f .95 video camera lens is used to image the small infrared LED targets located on the shuttle onto the photodiode detector. The LED's are multiplexed for target identification. A microprocessor located in the camera interface controls the sequencing of the LED's and data transfer to the PC.

Position and Attitude Determination

The position and attitude of the SCOLE platform is defined by six parameters; the x , y , z location of the center-of-mass of the shuttle in the fixed (laboratory) reference frame, denoted x_{cm} , y_{cm} , and z_{cm} , and the Euler angles, ψ , θ , and ϕ (fig. 4). These six parameters are determined by solving a set of nonlinear equations which relate the measured x - y camera coordinates of the six target LED's to the position and attitude of the (rigid body) platform. This set of nonlinear equations is derived by substituting the three equations

$$\begin{aligned} x_{fj} = & x_{cm} + x_{bj}(\cos(\theta) \cos(\psi)) + y_{bj}(-\cos(\phi) \sin(\psi) + \sin(\phi) \sin(\theta) \cos(\psi)) \\ & + z_{bj}(\sin(\phi) \sin(\psi) + \cos(\phi) \sin(\theta) \cos(\psi)) \end{aligned} \quad (3a)$$

$$\begin{aligned} y_{fj} = & y_{cm} + x_{bj}(\cos(\theta) \sin(\psi)) + y_{bj}(\cos(\phi) \cos(\psi) + \sin(\phi) \sin(\theta) \sin(\psi)) \\ & + z_{bj}(-\sin(\phi) \cos(\psi) + \cos(\phi) \sin(\theta) \sin(\psi)) \end{aligned} \quad (3b)$$

$$z_{fj} = z_{cm} + x_{bj}(-\sin(\theta)) + y_{bj}(\sin(\phi) \cos(\theta)) + z_{bj}(\cos(\phi) \cos(\theta)) \quad (3c)$$

into the photogrammetric collinearity equations (ref. 3)

$$x_{ij} = x_{pi} + f_i \left[\frac{m_{11}(x_{fj} - x_{ci}) + m_{12}(y_{fj} - y_{ci}) + m_{13}(z_{fj} - z_{ci})}{m_{31}(x_{fj} - x_{ci}) + m_{32}(y_{fj} - y_{ci}) + m_{33}(z_{fj} - z_{ci})} \right] \quad (4a)$$

$$y_{ij} = y_{pi} + f_i \left[\frac{m_{21}(x_{fj} - x_{ci}) + m_{22}(y_{fj} - y_{ci}) + m_{23}(z_{fj} - z_{ci})}{m_{31}(x_{fj} - x_{ci}) + m_{32}(y_{fj} - y_{ci}) + m_{33}(z_{fj} - z_{ci})} \right] \quad (4b)$$

Equation 3(a-b) describes the transformation from body-frame coordinates (x_{bj}, y_{bj}, z_{bj}) to fixed-frame coordinates (x_{fj}, y_{fj}, z_{fj}) for a point j on a rigid body in terms of the location of the center-of-mass and the Euler angles. The collinearity equations describe the transformation from fixed-frame coordinates to camera-frame coordinates, where x_{ij} and y_{ij} are the coordinates of point j in camera i ; x_{pi} and y_{pi} are the principal points of camera i ; f_i is the focal length of lens i ; x_{ci} and z_{ci} are the coordinates of the projective center of camera i in the fixed frame; and the m elements are components of the rotation matrix and are functions of the camera pointing angles ω_i , Φ_i , and κ_i . By substituting equations 3(a-c) into equations 4(a-b), the camera coordinates for any point on the rigid body are expressed in terms of the rigid-body position and attitude. The remaining terms in these equations, which include the camera parameters and body-frame coordinates of the point, are constant and determined beforehand by calibration. Photogrammetric resection and triangulation techniques are used to determine the locations and pointing angles of the cameras.

A total of 24 equations describe the x and y projections of the six LED's in the two cameras. These equations are linearized using a Newton's approximation, and a solution for the position and attitude of the SCOLE, defined by the six parameters, x_{cm} , y_{cm} , z_{cm} , ψ , θ , and ϕ , is obtained by using an iterative least squares technique. A flowchart of the tracking algorithm is shown in figure 5.

In the tracking technique described above, successive position and attitude estimates are not independent of one another. Since each solution is used as the starting point in

determining the next solution, how quickly the algorithm converges will depend upon the difference between the initial guess (the previous estimate) and the true answer. The magnitude of the error associated with the initial guess and the magnitude of the positional change in the SCOLE from one sample time to the next will determine how great this difference is. An obvious difficulty with this approach is that, should one or both of the sensors be temporarily lost during an experiment, it would be extremely difficult, if not impossible, to relocate the model without interrupting the run and stopping the motion. This could be overcome by incorporating an additional linear tracking method such as the one discussed in reference 5. The advantage in using the nonlinear approach discussed in this paper is that this algorithm provides a more accurate estimate of shuttle attitude.

In order to determine whether or not it would be possible to track the model from one sampling time to the next, experiments were conducted in a separate optics laboratory. There, it was demonstrated that convergence to less than a degree can be achieved in a single iteration with a signal-to-noise ratio of approximately 200, where the signal-to-noise ratio is defined as

$$\text{signal-to-noise} = \frac{\text{Maximum sensor signal (volts)}}{\text{RMS voltage of noise}}$$

and for a change in SCOLE attitude (yaw) of 2° between sampling intervals (fig. 8(a)). Studies have shown that, provided the frequency response of the sensing system is greater than about 10 samples/sec, the change in the (yaw) attitude of the SCOLE would not exceed 2° during any sampling interval (ref. 1).

Inherent in the above derivation is the assumption that the model is constrained to roll and pitch movements of less than 90° . An ambiguity arises should the pitch or roll exceed 90° . Several algorithms have been developed in robotics for tracking the unconstrained motion of a rigid body where this ambiguity has been overcome (ref. 4). However, in the present application, it is unnecessary to use more involved tracking techniques, as the

maximum pitch and roll angles of the SCOLE platform are constrained by the laboratory setup to less than $\pm 20^\circ$.

Camera Calibration

Careful calibration of the sensor and optics is required to produce the desired accuracy in the estimate of the SCOLE attitude. Lateral effect photodiodes such as the UDT (i.e., all four electrodes on the same side) will, due in part to the geometry of the electrodes, exhibit a nonlinear response outside the central region of the detector. For fixed amplifier gains and offsets, this distortion is fixed and, thus, by mapping the response of the detector, is quantified and a correction established. In addition to the distortion introduced by the nonlinear response of the sensor, there is distortion which arises from the optics. This optical distortion is also quantified through calibration.

Detector Response

To map the response of the detector and establish a correction for sensor distortion, a 0.028 inch (0.7 mm) diameter, filtered, HeNe laser beam is scanned over the surface of a diode and the output from the four electrodes recorded. (A neutral density filter is used to limit the light intensity.) A two-axis beam steering system with computer interface is used to scan the laser beam over the surface of a diode. The outputs of the sensor and scanner are recorded for 900 different x - y positions arranged in a 30×30 matrix. Random sensor and scanner errors are removed by averaging 60 scans. In figure 6, the measured x and y outputs of a sensor are graphed as a function of the x and y scanner coordinates. It is clear from figure 6 that the sensor response is not linear over the entire surface.

A distortion correction is determined by fitting the sensor data, using least squares, to the scanner data (the scanner beam positions are known to better than ± 0.0001 in.). A transformation of the form

$$x' = a_1 + a_2x + a_3y + a_4xy + a_5x^2 + a_6y^2 + a_7x^2y + a_8xy^2 + a_9x^3 + a_{10}y^3 \quad (5a)$$

$$y' = b_1 + b_2x + b_3y + b_4xy + b_5x^2 + b_6y^2 + b_7x^2y + b_8xy^2 + b_9x^3 + b_{10}y^3 \quad (5b)$$

is used to relate the normalized x, y beam positions derived from sensor data to the x', y' scanner beam positions (in inches). The transformation coefficients are saved and used to correct subsequent x and y sensor data.

Lens Calibration

A lens calibration is performed for two reasons, to determine the location of the sensor relative to the perspective center of the camera, by determining the locations of the principal points, x_p, y_p , and the location of the projection of the perspective center on the sensor, x_o, y_o ; and to determine a correction for optical distortion. The points x_p, y_p, x_o, y_o are determined by using the techniques described by Burner and Snow in reference 6. To determine the principal points, a laser is aligned (with lens removed) perpendicular to the sensor plane. The location of the image of the laser beam corresponds to the principal points, x_p, y_p . To determine the projection of the prospective center on the sensor, x_o, y_o , the laser is aligned perpendicular to the plane of the lens and imaged onto the sensor. The image location defines x_o, y_o . To correct lens distortion, a model developed by Brown (ref. 7) is used

$$\begin{aligned} \Delta x = \bar{x} & \left(l_1 r^2 + l_2 r^4 + l_3 r^6 \right) \\ & + \left(1 + p_3 r^2 \right) \left(p_1 \left(r^2 + 2\bar{x}^2 \right) + 2p_2 \bar{x}\bar{y} \right) \end{aligned} \quad (6a)$$

$$\Delta y = \bar{y}_j \left(l_1 r^2 + l_2 r^4 + l_3 r^6 \right) + \left(1 + p_3 r^2 \right) \left(p_2 \left(r^2 + 2\bar{y}^2 \right) + 2p_1 \bar{x}\bar{y} \right) \quad (6b)$$

where Δx and Δy are the corrections to the sensor coordinates, $\bar{x} = x' - x_p$ and $\bar{y} = y' - y_p$, previously corrected for sensor distortion, and referred to the principal points x_p and y_p , and $r^2 = (\bar{x}^2 + \bar{y}^2)$. To quantify the optical distortion, a calibration fixture consisting of a plane of diodes arranged in a 6×7 matrix is used. A single camera is positioned with the lens parallel to the fixture, and the positions of each diode are averaged over 60 frames and recorded. The locations of the diodes in the object field are known to better than 0.05 in. The known x - y locations of the diodes are fit to the corrected sensor x - y values to determine the l , and p coefficients for the camera.

Results and Discussion

The tracking accuracy of the SCOLE attitude sensing system has been evaluated through experiments conducted in a separate optics laboratory. A sensor geometry like that actually used in the SCOLE was maintained in the laboratory. A model of the SCOLE was attached to a computer controlled precision rotary stage, with a resolution of 0.001° , to allow movement in yaw (fig. 7). Figure 8 shows graphs of yaw angle measured by the optical system versus yaw angle measured by the rotary stage. In figure 8(a), the displacement in yaw was 2° per sampling interval. In figure 8(b), the yaw displacement was 0.5° per sampling interval. The slope is not equal to one in either case as the plane of the diodes was not perfectly parallel to the rotary stage. The variance of the data about a line fit through the data is 0.08° for figure 8(a), and 0.02° for figure 8(b).

The data presented in the graphs of figures 8(a) and (b) are the result of averaging over several scans. At present, the random noise of the sensors is relatively high. Multiple scans are averaged in order to achieve a greater accuracy in the position and attitude estimate. However, averaging over several scans reduces the frequency response of the

optical measurement system. A solution to this problem is currently being implemented; the existing diodes are being replaced with more powerful diodes and the gain on the amplifiers is being reduced, thereby improving the signal-to-noise ratio. With this upgrade, it is anticipated that the optical attitude sensing system will operate in excess of the required 10 samples/sec, and have an accuracy at least as high as that achieved with the present system using multiple scans.

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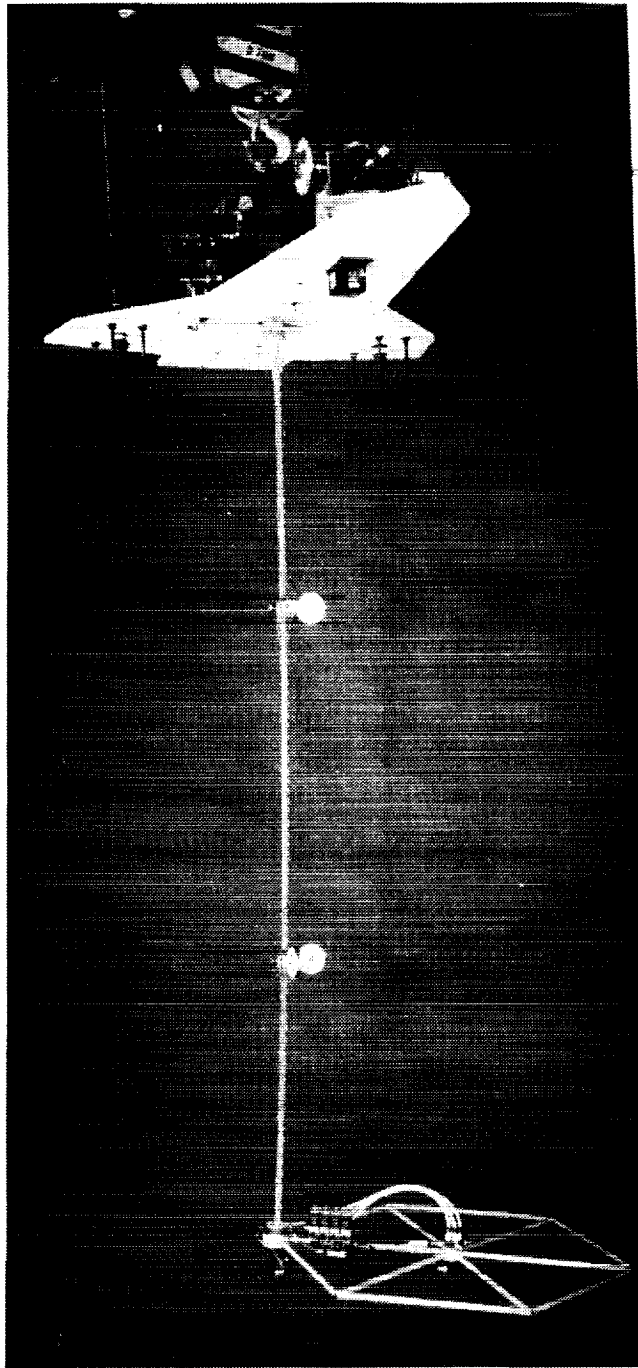
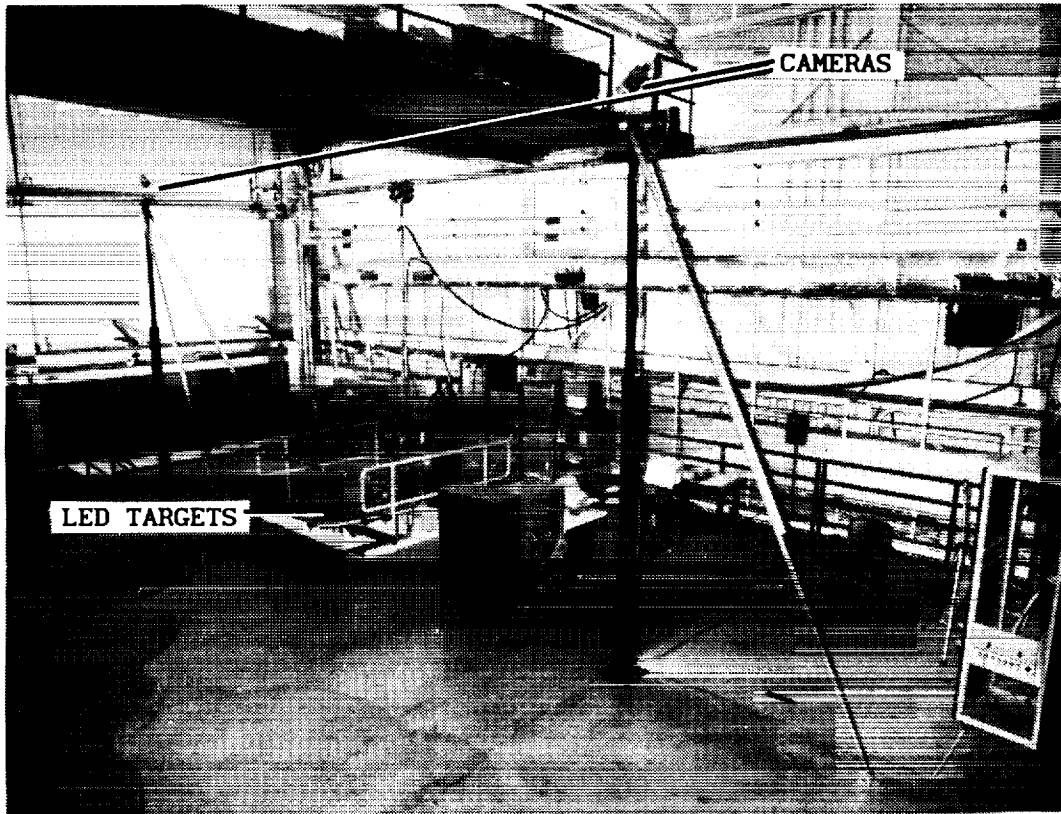
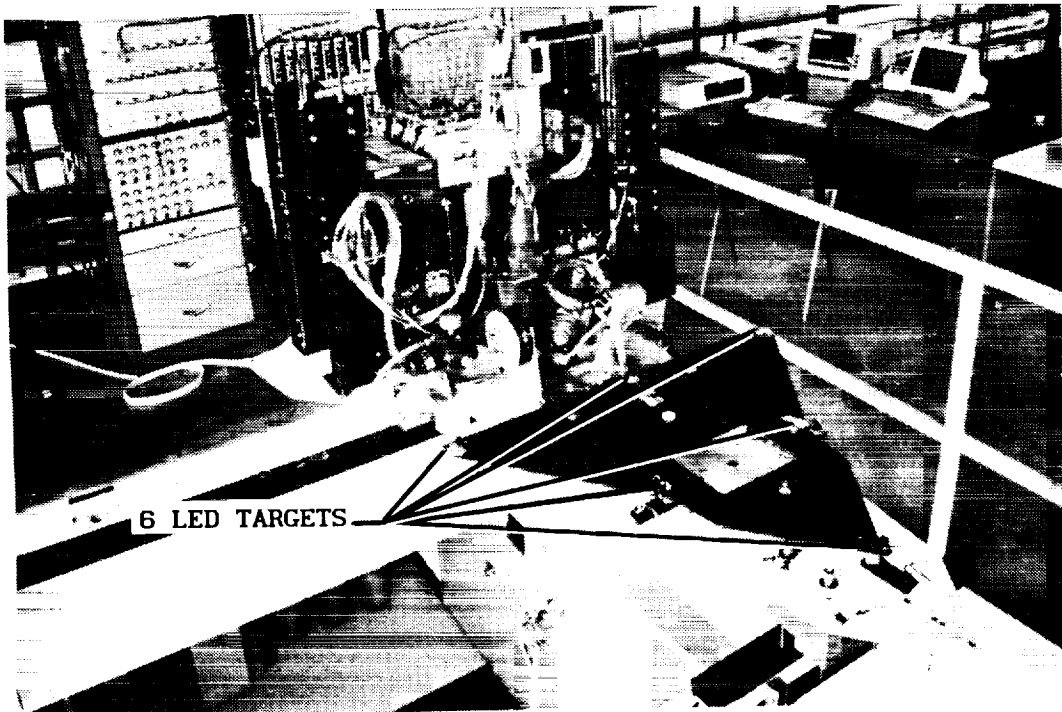


Figure 1. Picture of the shuttle platform and flexible antenna of the Spacecraft Controls Laboratory Experiment (SCOLE).



(a)



(b)

Figure 2. (a) Photograph of SCOLE optical attitude measurement system. (b) Closeup photograph of the shuttle platform showing LED targets.

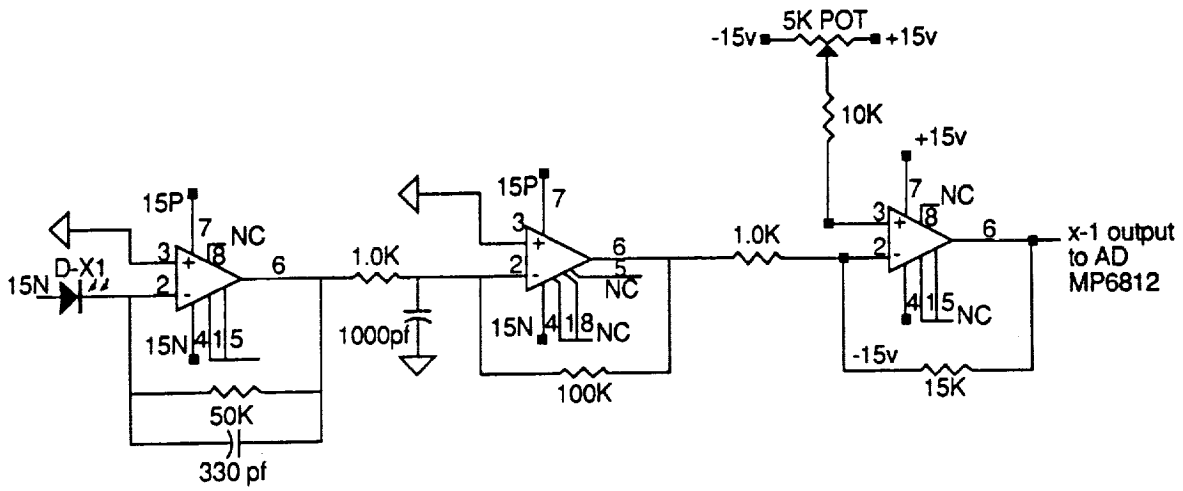


Figure 3. (a) Circuit diagram of camera electronics. One channel is shown. There are four channels per camera.

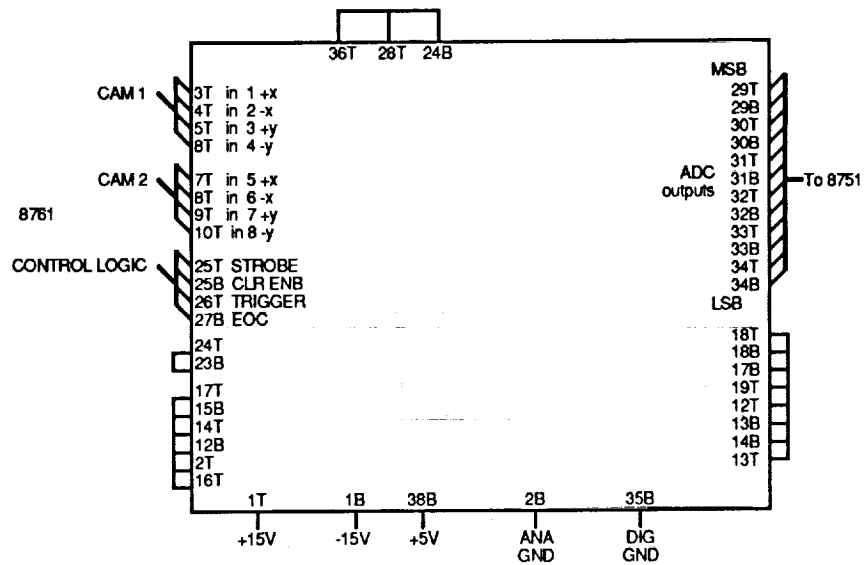
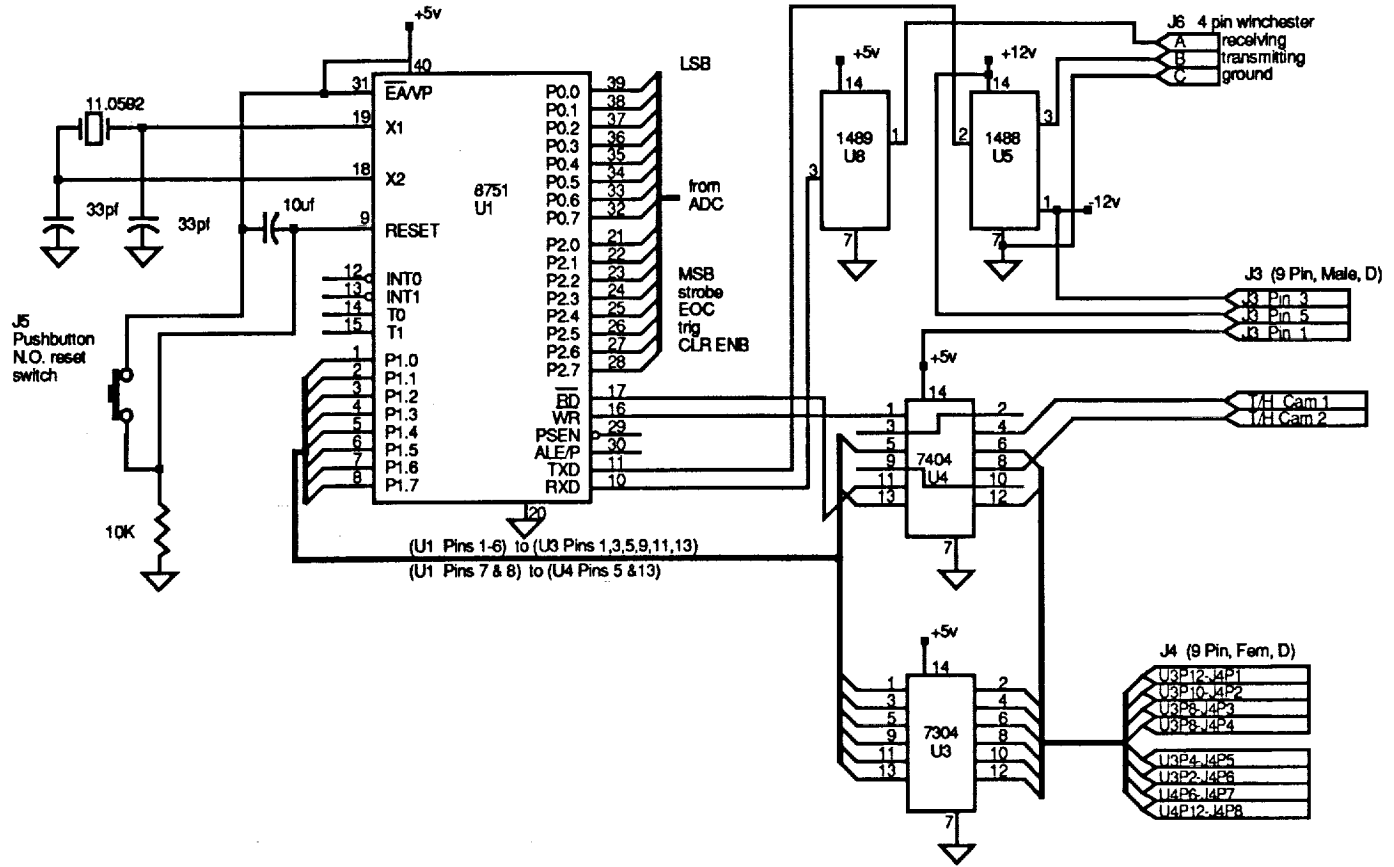
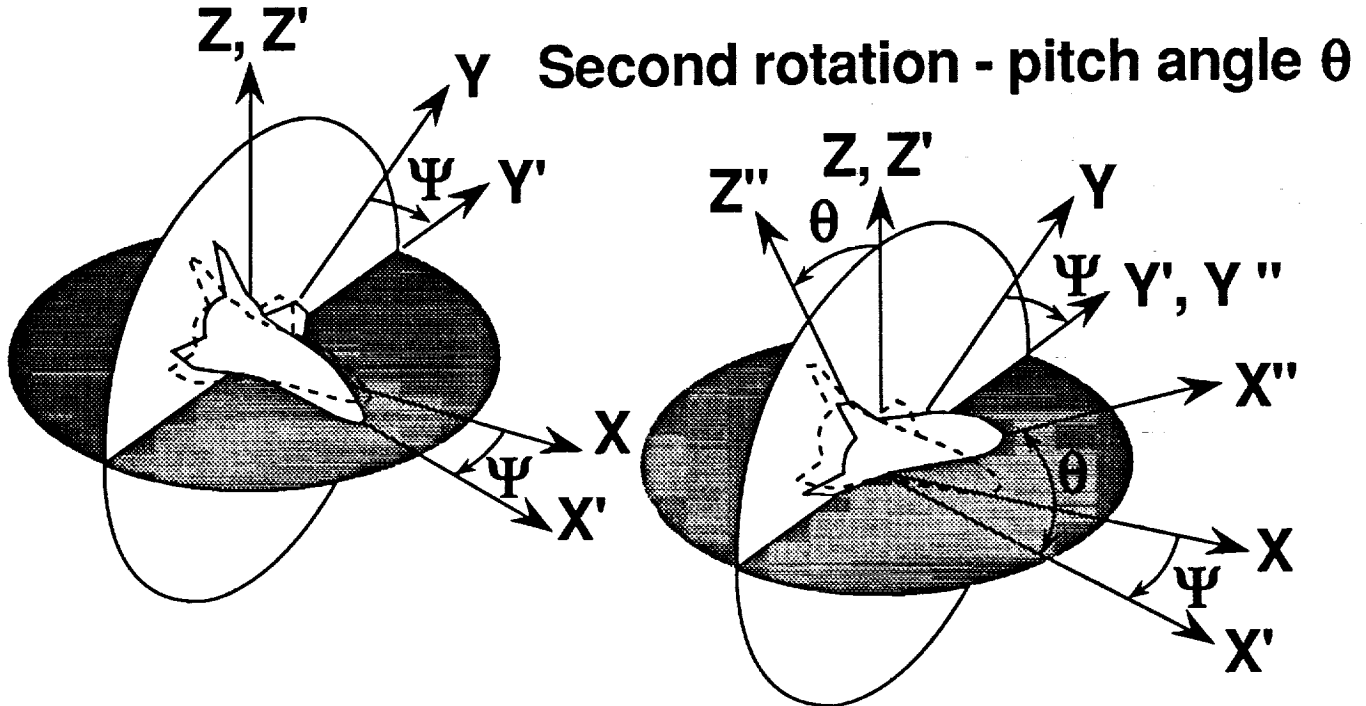


Figure 3. (b) Circuit diagram of (serial) computer interface.

First rotation - yaw angle Ψ



Third rotation - Roll angle Φ

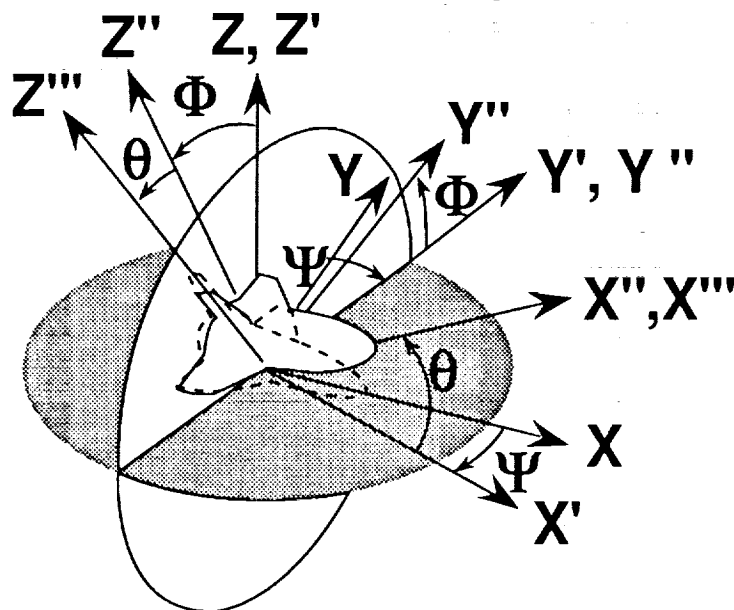


Figure 4. Definition of Euler angles ψ, θ, ϕ .

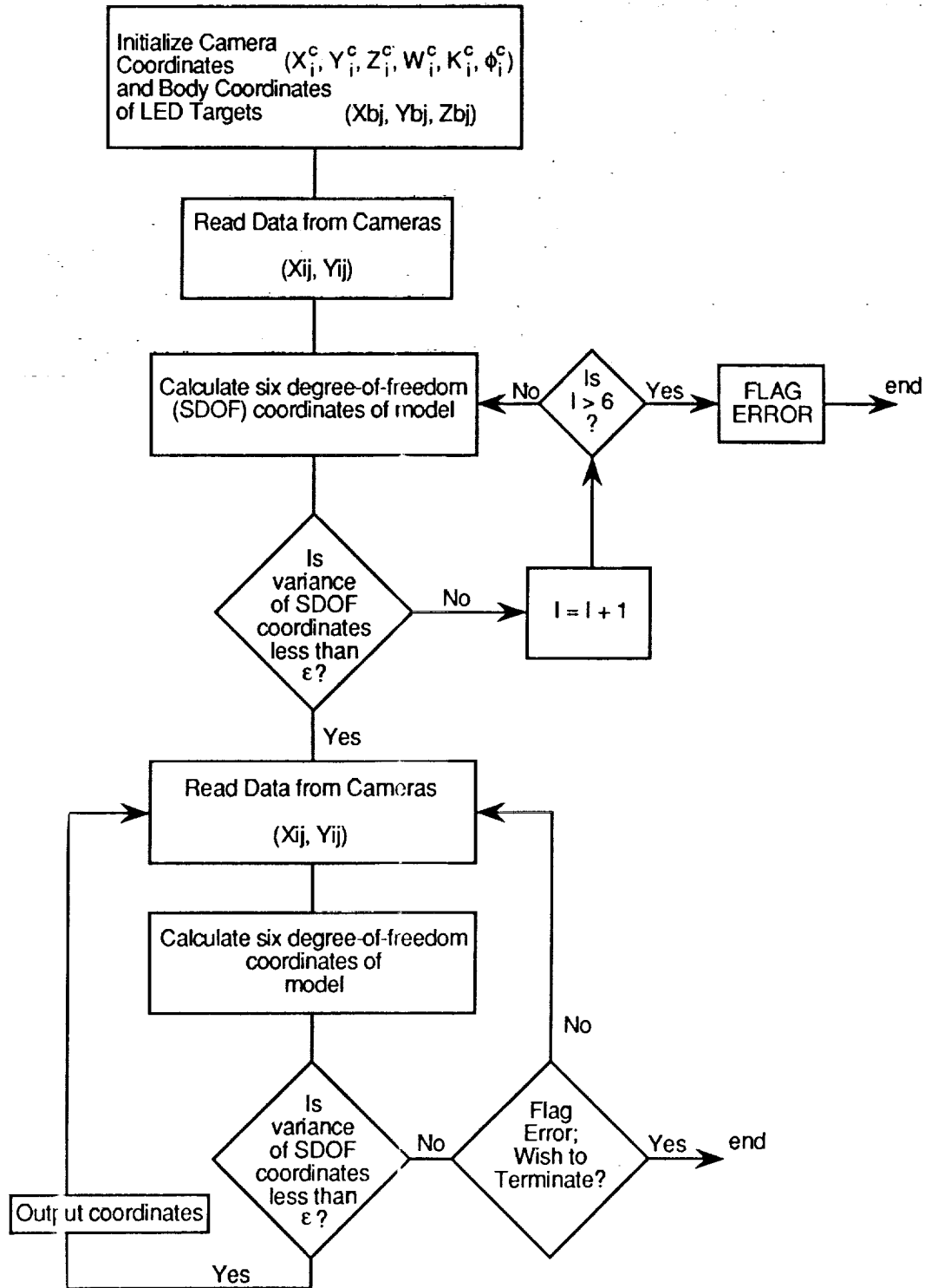


Figure 5. Flowchar of tracking algorithm.

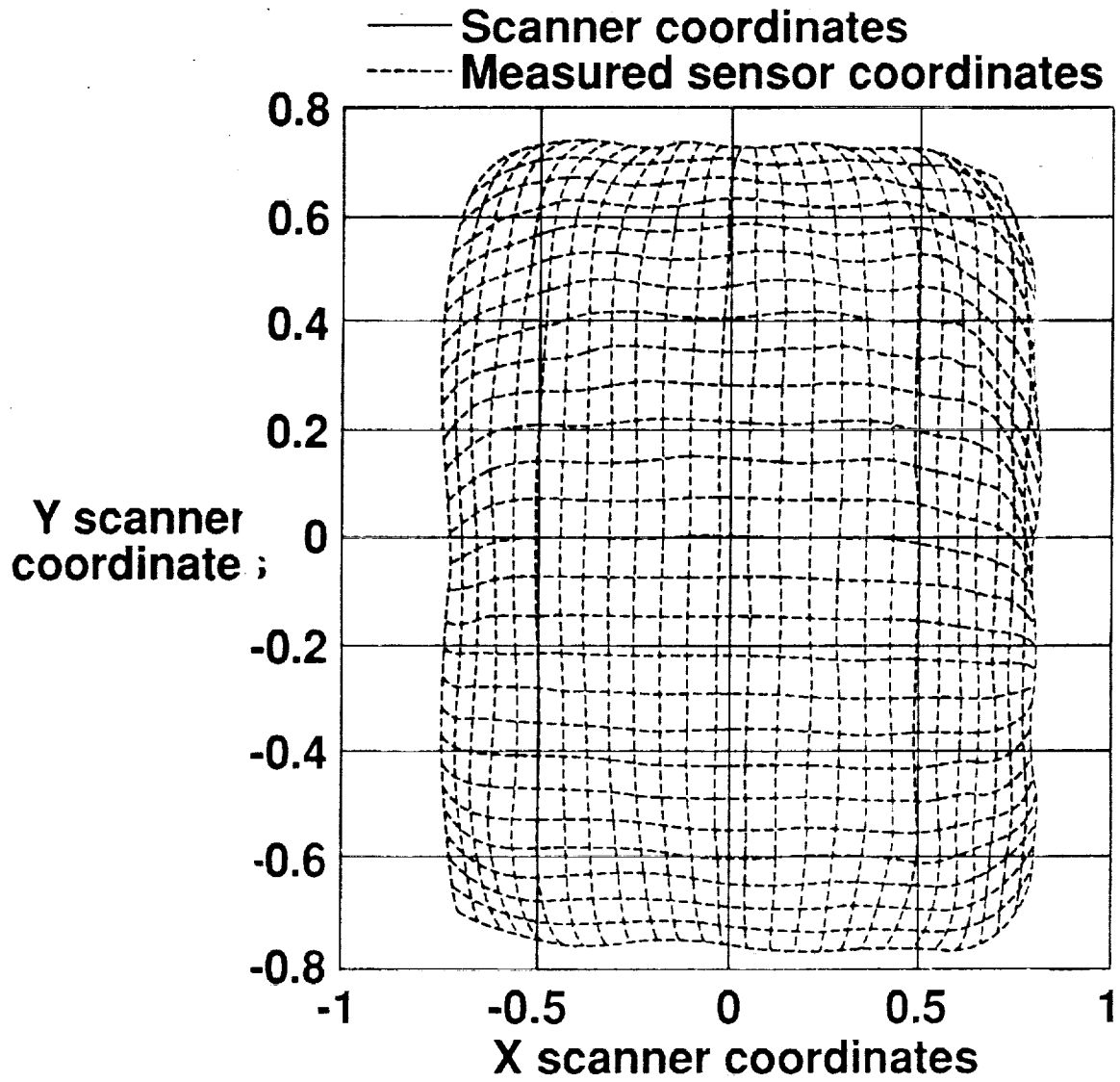
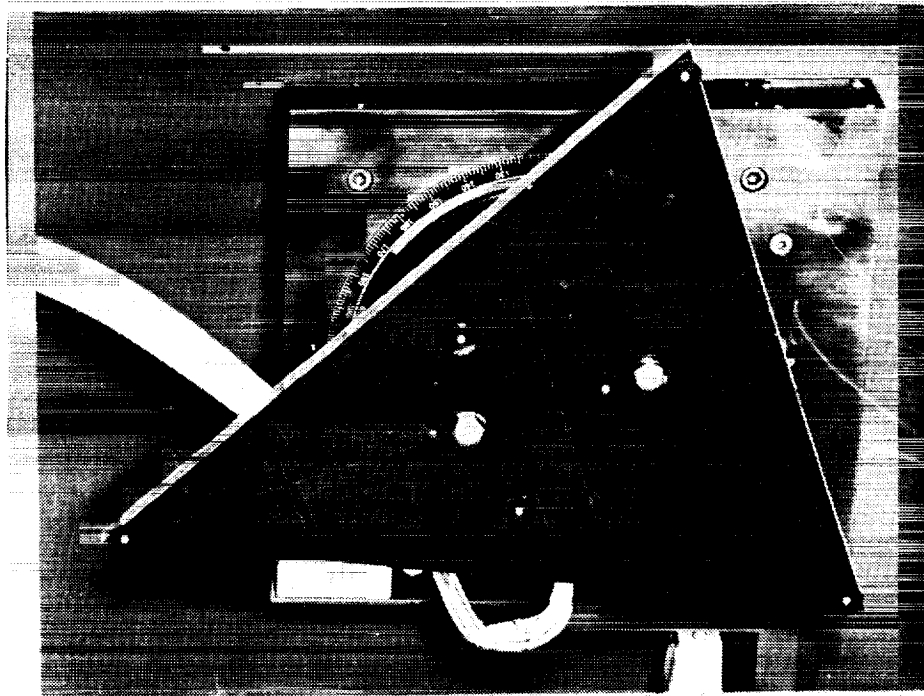
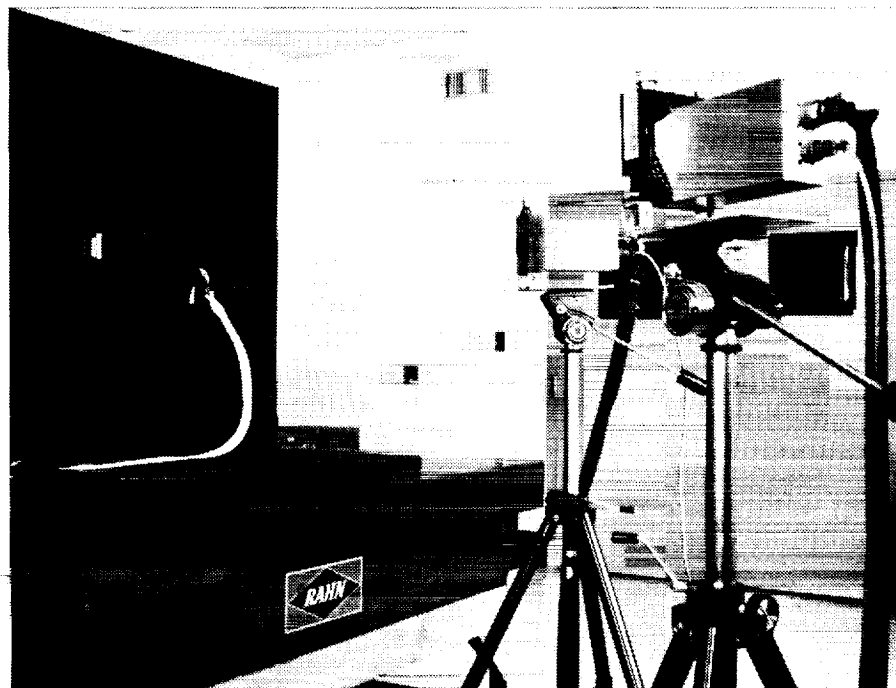


Figure 6. Sensor output versus output of beam scanning system.



(a)

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(b)

Figure 7. Pictures of (a) rotary stage and SCOPE model and (b) laboratory setup.

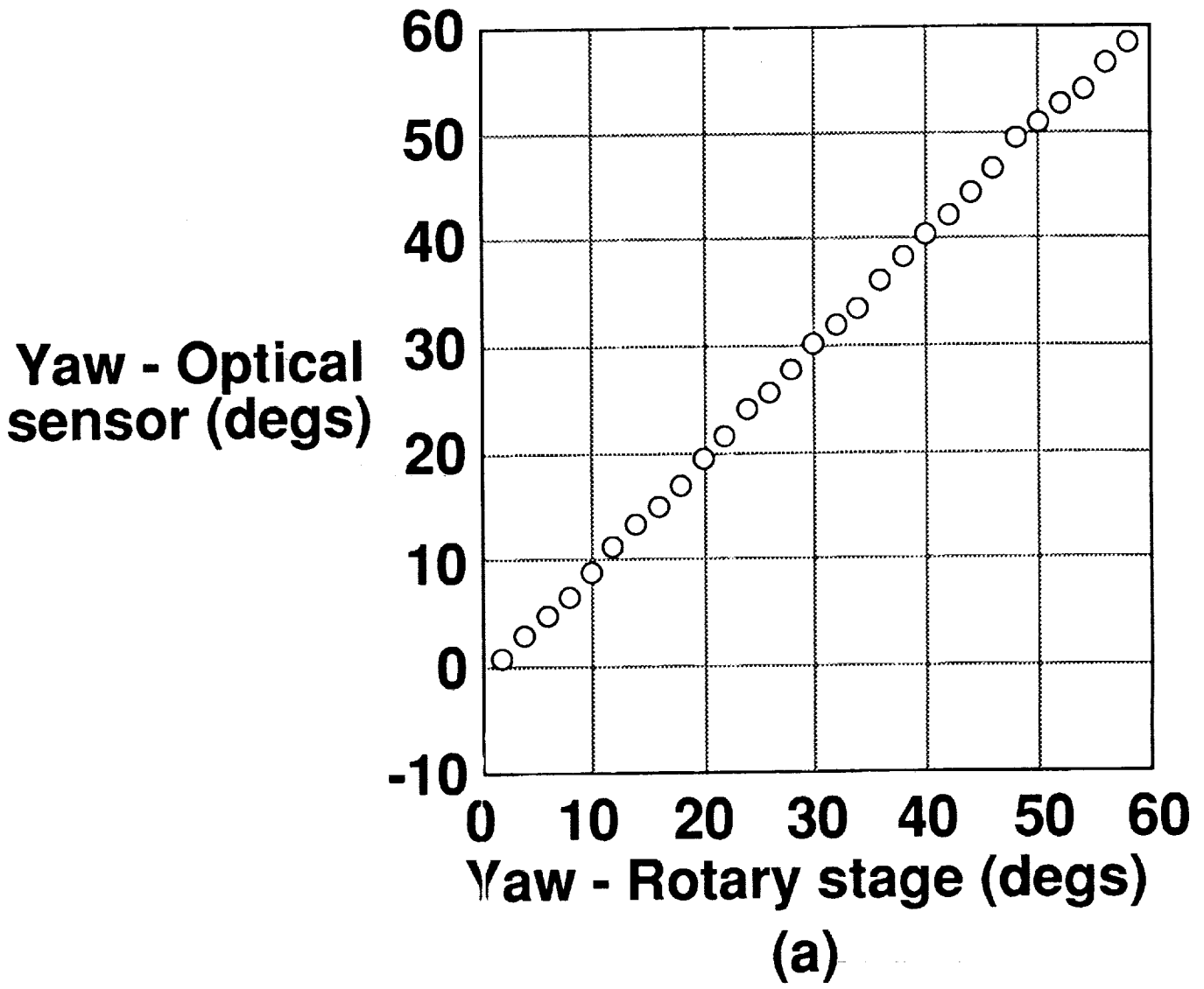


Figure 8. (a) Yaw estimate versus position of rotary stage; 2.0° increments between measurements.

**Yaw - Optical
sensor (degs)**

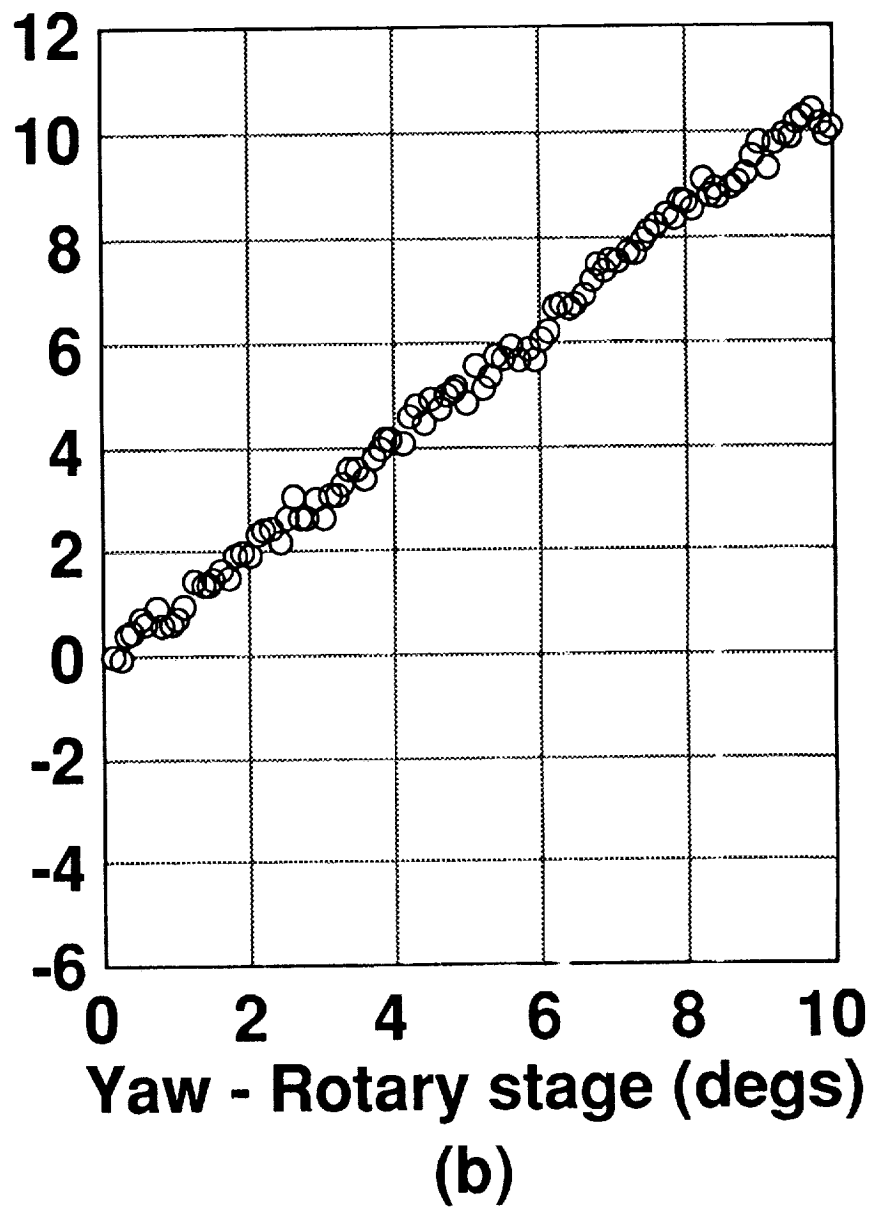


Figure 8. (b) Yaw estimate versus position of rotary stage; 0.5° increments between measurements.



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