POSITION REFERENCE SYSTEM

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ABSTRACT

This paper presents various algorithms and techniques to test the performance of laser tracking systems by means of video cameras. An efficient way of calibrating cameras is also presented. The state vector of a target - which gives information about the position, orientation, linear and angular velocities, linear and angular accelerations, and track of the target - will be determined.

1 INTRODUCTION

The *Position Reference System* (PRS) is a calibration and test facility for laser tracking systems, which is being built at the Lyndon B. Johnson Space Center (JSC), NASA. The PRS is intended for the calibration of tracking systems to be used for *docking* and *rendezvous*, especially for docking the Shuttle with the Space Station. The objective is to design a system, using passive sensors, to determine the state vector of a target and to compare this data with that of the laser sensor. Currently, all docking and rendezvous operations are accomplished manually by means of radar. NASA will replace this present manual operation with an automatic one. The automatic operation, or the laser tracking system, will use a low power laser beam to track a target and feed data into the main computer of the Shuttle.

The laser tracking system will lock onto a target equipped with optical retroreflectors by illuminating the retroreflectors and determine the state vector of the target. For laboratory experiments, the target will be held by a robot. The robot, controlled by a personal computer at the console, will perform various test maneuvers. It is designed to run on a roughly horizontal floor of a tunnel, and is capable of rotating around an axis perpendicular to the floor.

In the PRS laboratory (Fig. 1), the robot will be monitored by *eleven* monochrome charge-coupled device (CCD) video cameras located in the ceiling so as to provide overlapping fields of view (FOV). Self-illuminated targets or bright miniature lamps (i.e., the PRS targets) on top of the robot, placed in a right-angled triangular configuration, will enable the video and data processing systems to give the precise location of the laser sensor's target. The PRS system is designed to be a secondary/standby system in case the laser tracking sensor either fails to determine the state vector of the target or gives erroneous results. This is achieved by comparing the outputs from the two systems.

This paper is organized into three main sections, namely: (i) Hardware Configuration, (ii) Mathematical Modeling, and (iii) Experimental Results. Each section will be discussed separately.

2 HARDWARE CONFIGURATION

The hardware is essentially divided into three major units: (a) The Tracking System, (b) the Target Assembly and (c) the Surveying System. The *Tracking System* (Fig. 2) has various components required to track a target (a robot carrying three bright lights or *PRS targets*). The image from one of the cameras, selected by a computer controlled video switch unit, is first digitized by a frame grabber. This image is displayed on a monochrome monitor and fed to the main computer. Software is written, based on mathematical modeling of the system to be discussed later, to search for and track the PRS targets. The main computer does all the main computations for these operations and determines the state vector. The results can be either plotted or printed out for later analysis. The system has the capability of locating the targets automatically by switching between different camera's FOV. An appropriate camera can also be selected manually by means of a pointing device (e.g., a mouse).

The *Target Assembly* (Fig. 3) has two main components: the robot that carries the target, and the control unit that comprises a host computer, a joystick, an RF modem, and an antenna. The host computer is connected to the joystick through a 9600 baud serial port. The output of the joystick is in turn connected to the modem by means of a cable. This modem allows communications, by means of an antenna situated above surrounding equipment and away from any wiring, with the robot. This data link is referred to as the *Supervisory link*. A second serial network, called the *Control link*, exists inside the vehicle, which is mastered by the on-board computer.

The *Surveying System* (Fig. 4) is a real-time measuring system that has optical and computer technologies combined together to measure/calculate, display, and record alignment and metrology data for industrial applications reliably and accurately. This system comprises the computer system, with a printer, and two high-precision digital theodolites. These theodolites are used to establish any user-defined XYZ coordinate system, or a reference system and to determine the 3-D coordinates of spatial points with respect to this reference system. This system is used for surveying special *optical targets* (or *calibration marks*) that are laid on the floor in a particular fashion. This is done in order to calibrate the CCD cameras and will be discussed in section 3.2.1.

3 MATHEMATICAL MODELING

Fig. 5 shows the flow chart for the PRS software development. When the PRS program starts executing, one of the cameras starts looking for the PRS targets (three bright spots with a dark background, the whole assembly being carried by a remote-controlled robot) in the scene. The target acquisition can be done in two ways: manually and automatically. The appropriate camera can be turned *on* to look for PRS targets in *search* mode if the operator knows their locations *a priori* . Otherwise, the cameras will be turned *on* automatically, one after another. This process will take considerably more time than selecting and turning *on* the cameras manually. The 2-D image coordinates (x,y) of the targets are changed to floor co-ordinates (u,v) by mapping out the optical and video distortion effects and other errors. Off-line processing is done in order to calibrate each camera. For this purpose, the 3-D floor coordinates relative to a *reference* co-ordinate system and their corresponding 2-D image coordinates in a particular camera's FOV of circular optical targets, placed on the intersections of a 1- by 1- m grid are measured with an additional target at the center of each individual grid. A least-squares fitting of this data yields a set of mapping cefficients for each camera that account for the lens distortions and other errors.

Once the PRS targets are found, the PRS program begins tracking the target(s). The program automatically tracks the robot by storing the 2-D video coordinates of the PRS target(s) in real-time, and by switching between the cameras if the robot moves from one camera's FOV to another. If the program loses track of the robot, it will automatically go back to search for the PRS targets. The operator can then do some off-line processing to map (x,y) coordinates to (u,v) coordinates; compute linear and angular velocities and accelerations; print and plot this data for later analysis. The operator can terminate execution of the PRS program at any stage in the program.

3.1 OPERATING MODES

The PRS program essentially works in five distinct operating modes (Fig.3.3). Table 1 gives a brief description of the different operating modes that have been used in the PRS program :

Table 1: Different Operating Modes

Mode No.	Mode Name	Description
0	IDLE	Not operating
1	CALIBRATE	"Off-line" geometric calibration
2	SEARCH	Search for the PRS targets

3	TRACK	Track the targets, store/update image co-ordinates of targets on the hard disk of the main computer
4	PRINT/GRAPH	Print/plot the data as a function of time

Modes 1,2 and 4 are entered and exited from/to mode 0 manually. Mode 3 can only be entered automatically only from mode 2. Mode 3 can be exited manually to mode 0. In other words, the operator can exit from any mode to mode 0 manually.

3.1.1 IDLE Mode

This mode indicates an *idle state* as no operations are performed in this mode. The PRS software accepts keystrokes to enter other modes.

3.1.2 CALIBRATE Mode

In this mode, the software determines the image coordinates (x,y), in a particular camera's FOV, of optical targets whose precise (u,v) locations are known. The (u,v) coordinates are entered once by the operator and is used along with the (x,y) coordinates to determine the *geometric calibration coefficients* of the cameras. See section 3.2.1 for more details.

The calibration coefficients are stored in a historical file, and supplied to TRACK mode after the tracked image coordinates of the target(s) are stored in the main computer.

3.1.3 SEARCH Mode

The steps of operation in this mode are as follow:

Step 1: Grab a frame from the primary camera.

Step 2: Find brightest pixel. For this, we test each pixel as follows to determine if it could be a candidate target as follows:

a. Start at the first row plus a row offset.
b. Perform a *boundary test* on the first column plus a column offset. The boundary test calculates a background value in both the +/- horizontal direction and in both the +/- vertical direction. The background value is an average of several pixels which are located several more pixels away (3 for our analysis) from the pixel being tested. If the pixel being tested minus a given background value is more than the threshold value, the pixel has passed the boundary test for one direction. If the pixel passes the boundary test in each of the four directions then the pixel is considered a *candidate* target.
c. If the boundary test determines that the pixel is a target, check to see that it is not too close to the existing targets. If it is not too close, the pixel is accepted as another target. Search only every other column and every other row for targets.

Step 3: If too many targets were found, the threshold limit is increased and the image is searched for the target(s) again. This continues until either the correct number of targets is located or the upper threshold limit for the given camera is reached.

Step 4: If not enough targets were found, the threshold limit is decreased and the image is searched again for the target(s). This is continued until either the correct number of targets is located or the lower threhold limit for the camera is reached.

Step 5: If any other candidate targets have been located, check *inter-target* distances between each (known). The additional constraint of three targets to form a right-angled triangle should easily stop us from identifying a false target for our analysis.

Step 6: Designate the three targets found as target #1, target#2, and target #3. This can be done by considering the target opposite the largest side of the triangle they form as target #1, and so on.

When the targets are identified, three circles of different radii (smallest circle corresponding to target #1) should be drawn, and displayed, around each target so that the operator has an idea/confirmation of the valid targets.

3.1.4 TRACK Mode

Once the targets have been located, the PRS program will enter the TRACK mode. The following steps are performed:

Step 1: Only a small rectangle (currently 10 by 10 pixels) around the current location of the target is searched. If the target is found, the target position is updated and the tracking is continued. In order to achieve sub-pixel accuracy, we should compute the *pixel-value-weighted centroid* for each target, because the target may represent several bright pixels in the video.

Step 2: If the target is not found, the previous step willl be repeated several times.

Step 3: If the target is still not found, the entire camera's FOV will be searched for all the targets, i.e., it goes back into SEARCH mode. If the target is still not found, the program will automatically search the next closest camera. The program will continue switching between cameras until a target is located. At any time, the user may manually select a camera to be searched for the target via mouse input. Three circles of different radii should be drawn in order to verify/confirm the targets when searched.

Step 4: When in TRACK mode, if the target is close to the border of the primary camera, the program will automatically switch cameras.

Tracking continues until the user aborts.

3.1.5 PRINT/GRAPH Mode

In this mode, the state vector of a target as a function of time, can be printed out or plotted.

3.2 GEOMETRIC CORRECTIONS

A technique is presented to calibrate the CCD cameras off-line before any real testing of the algorithms is done to determine the state vector of the PRS targets.

3.2.1 Calibration of CCD Cameras

Each camera is characterized by some set of single-precision, floating-point coeffficients. These coefficients must be computed (in CALIBRATE mode) and the cameras must be calibrated accordingly before they are used for real-time analyses of images. Cameras are calibrated in order to determine the following:

a. The adequate calibration data for mapping out distortions (due to lens, perspective transformation/scaling, skewing, keystoning, etc.) and the possibility of data error.

b. The FOV for each camera and the region of overlap of two adjacent cameras.

c. Mapping coefficients for each camera used to convert 2-D image co-ordinates to floor co-ordinates.

Let (x,y) be 2-D image coordinates with the origin at the upper left corner of the image plane, the positive x-axis along the scan direction, and the positive y-axis downwards (Fig. 6). Let (u,v) be the floor coordinates with the origin directly under 6^{th} camera, the positive v-axis down the tunnel axis, and the positive u-axis across the tunnel from left to right when facing in positive v-axis direction.

The relationship between the floor coordinates (u_j,v_j) of optical targets in j^{th} (j = 1, 2, ... , 11) camera's FOV and their corresponding image coordinates (x_j,y_j) is shown by the following set of equations for *n* (n > 16) calibration points:

$$F_j = {}^{AB}\Gamma_j \, I_j \qquad (1a)$$

where the *floor matrix* F_j contains the floor coordinates of the floor targets (in j^{th} camera's FOV) as its elements, the *image matrix* I_j has the corresponding image coordinates as its elements, and the *coefficient matrix* ${}^{AB}\Gamma_j$ has the unknown *calibration coefficients* for the j^{th} camera. Only terms up to third-order are accepted in this calibration scheme. These matrices are

$$F_j = \begin{bmatrix} u_{1,j} & u_{2,j} & \cdots & u_{n,j} \\ v_{1,j} & v_{2,j} & \cdots & v_{n,j} \end{bmatrix} \qquad (1b)$$

$${}^{AB}\Gamma_j = \begin{bmatrix} A_{0,j} & A_{1,j} & \cdots & A_{n,j} \\ B_{0,j} & B_{1,j} & \cdots & B_{n,j} \end{bmatrix} \qquad (1c)$$

$$I_j = \begin{bmatrix} 1 & x_{1,j} & y_{1,j} & x_{1,j}^2 & y_{1,j}^2 & x_{1,j}^2 y_{1,j} & x_{1,j} y_{1,j}^2 & x_{1,j}^2 y_{1,j}^2 & x_{1,j}^3 & y_{1,j}^3 & x_{1,j}^3 y_{1,j} & x_{1,j} y_{1,j}^3 & x_{1,j}^3 y_{1,j}^2 & x_{1,j}^2 y_{1,j}^3 & x_{1,j}^3 y_{1,j}^3 \\ 1 & x_{2,j} & y_{2,j} & x_{2,j}^2 & y_{2,j}^2 & x_{2,j}^2 y_{2,j} & x_{2,j} y_{2,j}^2 & x_{2,j}^2 y_{2,j}^2 & x_{2,j}^3 & y_{2,j}^3 & x_{2,j}^3 y_{2,j} & x_{2,j} y_{2,j}^3 & x_{2,j}^3 y_{2,j}^2 & x_{2,j}^2 y_{2,j}^3 & x_{2,j}^3 y_{2,j}^3 \\ * & * & * & * & * & ** & * & & & & & & & * & * \\ 1 & x_{n,j} & y_{n,j} & x_{n,j}^2 & y_{n,j}^2 & x_{n,j}^2 y_{n,j} & x_{n,j} y_{n,j}^2 & x_{n,j}^2 y_{n,j}^2 & x_{n,j}^3 & y_{n,j}^3 & x_{n,j}^3 y_{n,j} & x_{n,j} y_{n,j}^3 & x_{n,j}^3 y_{n,j}^2 & x_{n,j}^2 y_{n,j}^3 & x_{n,j}^3 y_{n,j}^3 \end{bmatrix} \qquad (1d)$$

A least-squares fitting of (u,v) coordinates against (x,y) coordinates in the above equations directly yields the coefficients for each camera. In equation (3.1c), $(A_{0,j},B_{0,j})$ or $(u_{int,j},v_{int,j})$ represent the *shift* of the origin of the image coordinate system relative to the origin of the floor coordinate system; $(A_{1,j},B_{1,j})$ represent the *scale* factors along the x and y axes (*perspective transformation*); $(A_{2,j},B_{2,j})$ represent the *skew* factors (rotations) along the x and y axes; $(A_{3,j},B_{3,j})$ represent the *keystoning* factors along the x and y axes; and so on. Once the cameras are calibrated, the floor coordinates of the PRS targets are determined from a knowledge of their corresponding image coordinates and the calibration coefficients of the particular camera through which the targets are viewed. This type of mapping of (x,y) into (u,v) is called the *forward transformation* .

3.2.2 Forward Transformations

While the PRS target(s) is tracked, its tracked image coordinates are stored in the main computer real-time. The following set of equations convert camera (x,y) coordinates into floor-projected (u,v) co-ordinates:

$$u_j = [(A_{15,j}*xy + A_{14,j}*y + A_{13,j}*x + A_{8,j})*xy + (A_{12,j}*y + A_{7,j})*y + (A_{11,j}*x + A_{6,j})*x + A_{3,j}]*xy + [(A_{10,j}*y + A_{5,j})*y + A_{2,j}]*y + [(A_{9,j}*x + A_{4,j})*x + A_{1,j}]*x + u_{int,j} \qquad (2a)$$

and

$$v_j = [(B_{15,j}*xy + B_{14,j}*y + B_{13,j}*x + B_{8,j})*xy + (B_{12,j}*y + B_{7,j})*y + (B_{11,j}*x + B_{6,j})*x + B_{3,j}]*xy + [(B_{10,j}*y + B_{5,j})*y + B_{2,j}]*y + [(B_{9,j}*x + B_{4,j})*x + B_{1,j}]*x + v_{int,j} \qquad (2b)$$

where (x,y) are the tracked 2-D image coordinates and $xy = x_j * y_j$ (* denotes product). The order of the multiplications and additions is specified to minimize the computational error so that single-precision floating-point (real) arithmetic can be used.

3.2.3 Target-Height Correction

At this point, only the floor-projected target coordinates are known to us. It is so because the target plane is at some known height above the floor and the camera views these targets radially (Fig.7).

If, for a particular target, the following parameters are known:

H_j , the height of j^{th} camera
H_T, the height of the target ($H_T \ll H_j$)
(u_j,v_j), j^{th} camera's sub-point co-ordinates
(u,v), floor-projected target co-ordinates

the *height-corrected* co-ordinates (u_T,v_T) of the target (or *position*) can be found as:

$$u_T = \lambda_1 u + \lambda_2 u_j \text{ and } \qquad v_T = \lambda_1 v + \lambda_2 v_j \qquad (3a,b)$$

where

$$\lambda_1 = (H_j - H_T)/H_j \text{ and } \qquad \lambda_2 = H_T/H_j \qquad (3c,d)$$

3.3 State Vector Determination

The state vector of a PRS target(s) has various components: position, orientation, linear and angular velocities, and linear and angular accelerations. Since the robot, with PRS targets, is moving on a roughly horizontal floor capable of rotating around an axis perpendicular to the floor, a minimum of two PRS targets need to be tracked in order to be able to compute orientation, and angular velocity and acceleration of the targets. The floor in each camera's FOV is assumed to be a horizontal plane in our analysis.

4 EXPERIMENTAL RESULTS

4.1 PROCEDURE FOR CALIBRATION OF CCD CAMERAS

In order to calibrate the cameras, optical targets were laid on the tunnel floor as a 1- by 1-m grid with an additional target at the center of each grid. This procedure provided 60-65 optical targets under each camera's FOV. Actually, in order to demonstrate the operability of the system, targets were laid in such a way that only camera's 5,6 and 7 FOV's were covered. The origin of reference system was chosen somewhat directly at the center of camera 6's FOV and a target was kept on it. The 3-D locations of rest of the targets were carefully measured by means of high-precision digital theodolites with respect to this origin, and stored later. Their corresponding 2-D image locations were measured *manually* by following sequence of steps: switching *off* all the lights in the laboratory, shining light on each target one by one by a flash light, taking a snap shot from the camera the target is under, and measuring the 2-D location by the mouse. This
procedure is rather a crude way of measuring 2-D locations of the targets as opposed to a *cross-correlation* technique where sub-pixel accuracy could be achieved. The 3-D locations of the some of the optical targets (u, v, z) with their 2-D image locations (X, Y) under proper camera number (Camera#) and with designated PRS coordinates (prs_u, prs_v) are shown in Fig. 8(a) . All measurements were done in millimeters. The set of calibration co-efficients for cameras 5 are listed in Fig. 8(b).

4.2 TEST RESULTS

Various experiments were run under different conditions. The user has the option to track either *one* target or *two* targets. If one target is tracked; the user can get the information about the position, linear velocity and linear acceleration of the target; which can be later printed out or plotted. If two targets are tracked; in addition to position, linear velocities and linear accelerations of both the targets; one can compute orientation, angular velocity and angular acceleration of the targets as well. The print-outs and the plots of various test results should also demonstrate the camera-switching, if any. Figs. 9(a) and 9(b) are the plots demonstrating the camera switching between cameras 5 and 6 when only one PRS target was tracked and the robot rotated.

4.3 TECHNICAL SPECIFICATIONS

Table 2 gives technical specifications (at target height) of the PRS system.

Table 2: Technical specifications of PRS

Maximum *linear velocity* of the robot possible without losing track of the target(s)	460mm/sec (if one target tracked) 355mm/sec (if two targets tracked)
Maximum *angular velocity* possible without losing track of the target(s)	90^{o}/sec (if one target tracked) 55^{o}/sec (if two targets tracked)
Pixel size (camera # 6's video)	11.24mm x 9.56mm at the edges 10.93mm x 9.05mm at the center
Distance measured between two targets (random experiment)	9.713mm off at the center 7.834mm off at the edge (about 5% error)
Height of camera #5	4845.58325mm
Height of camera #6	4837.10825mm
Height of camera #7	4843.98175mm
PRS target height (all targets in one plane)	1096mm
Inter-target distances	192mm, 387mm, and 433mm

The errors in the determination of position co-ordinates are possible due to the following reasons:

(i) The floor under each camera's FOV is assumed to be horizontal plane. The floor height can, as a matter of fact, vary by about one centimeter or more under the same camera.

(ii) The calibration co-efficients of each camera are assumed to be constants. In fact, these values keep on changing as a function of time as temperature changes inside the laboratory can significantly expand or contract the floor surface as well as the beams on which the cameras are mounted.

(iii) Some human error is involved in measuring the image locations of the optical targets manually (as opposed to a cross-correlation technique). If we are one pixel off in our measurements, it will result in an error of 9 to 11mm at target height when we measure the position of the targets. Sub-pixel accuracy could be achieved though, but at the cost of the processing speed of the computer.

5 CONCLUSIONS

In this documentation the hardware configuration of the PRS has been discussed. A rigorous mathematical model has been presented. Algorithms for target acquisition from CCD camera images, calibration of cameras, and determination of the state vector has been developed. Various experiments were conducted and the results were both printed out and plotted. Some accuracy analysis on the data obtained was also done. Future developements in the PRS project should include a voice-controlled robot being tracked by a matrix of cameras, instead of an array of cameras.

6 ACKNOWLEDGEMENTS

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Fig. 1: PRS Laboratory (not available).

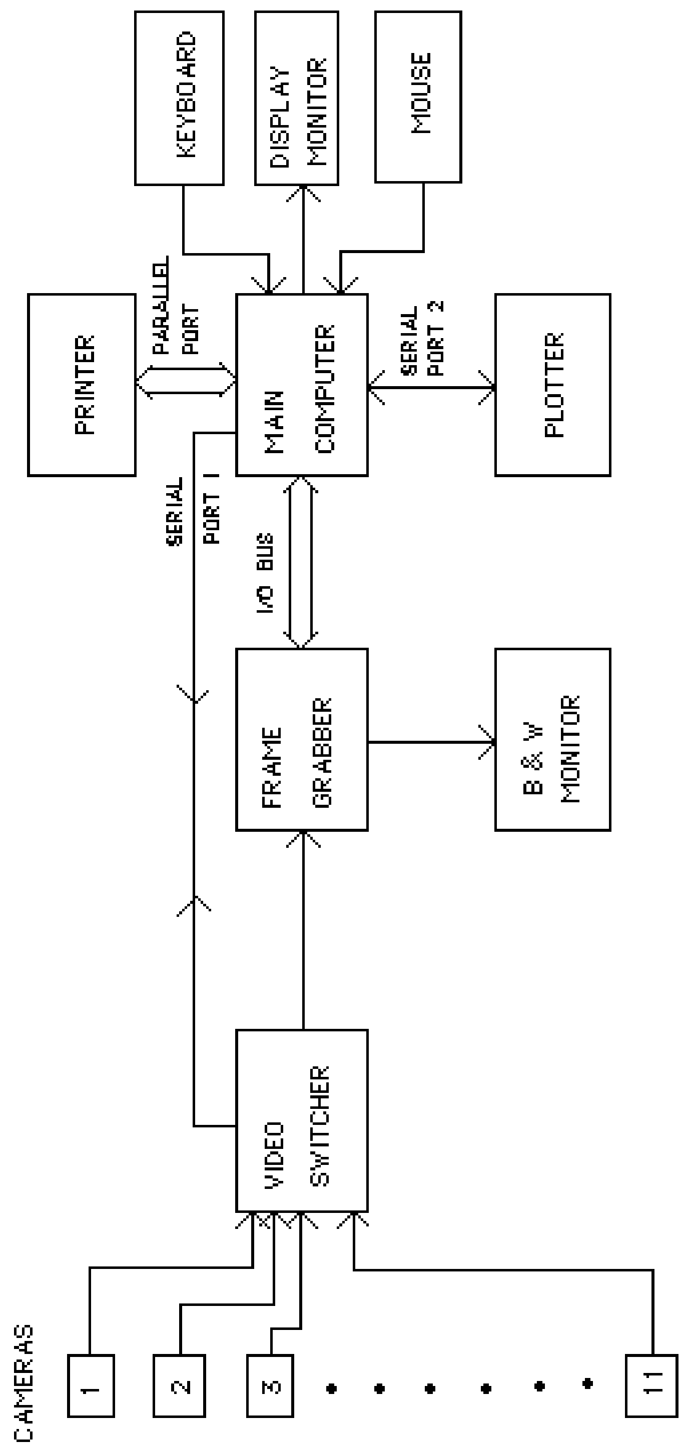

Fig. 2: Block diagram representation of the Tracking System.

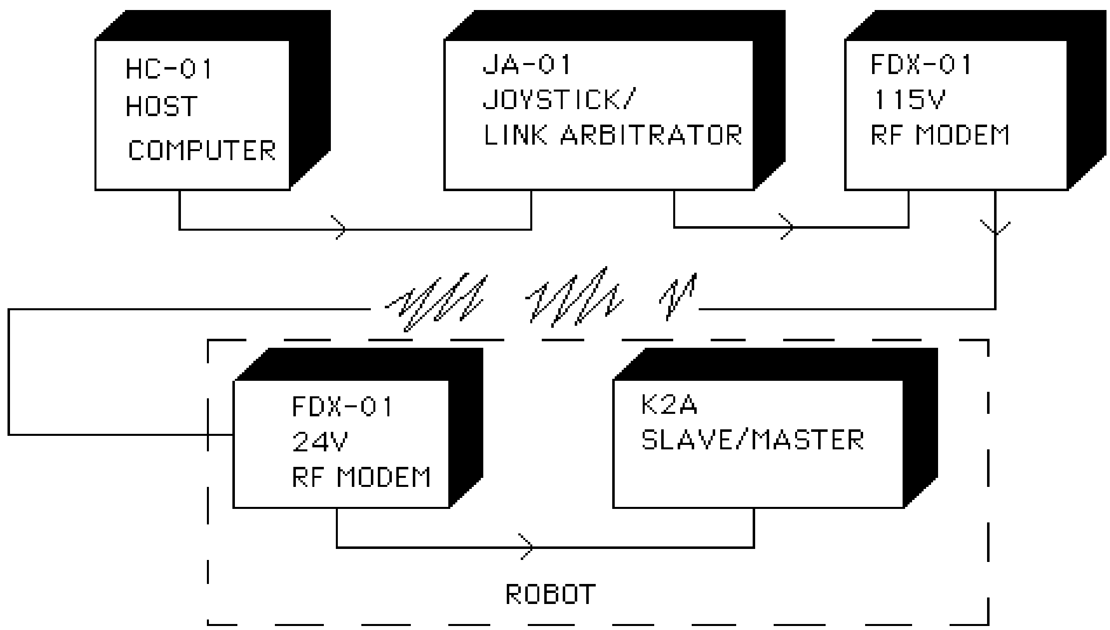

Fig. 3: Block diagram representation of the Target Assembly.

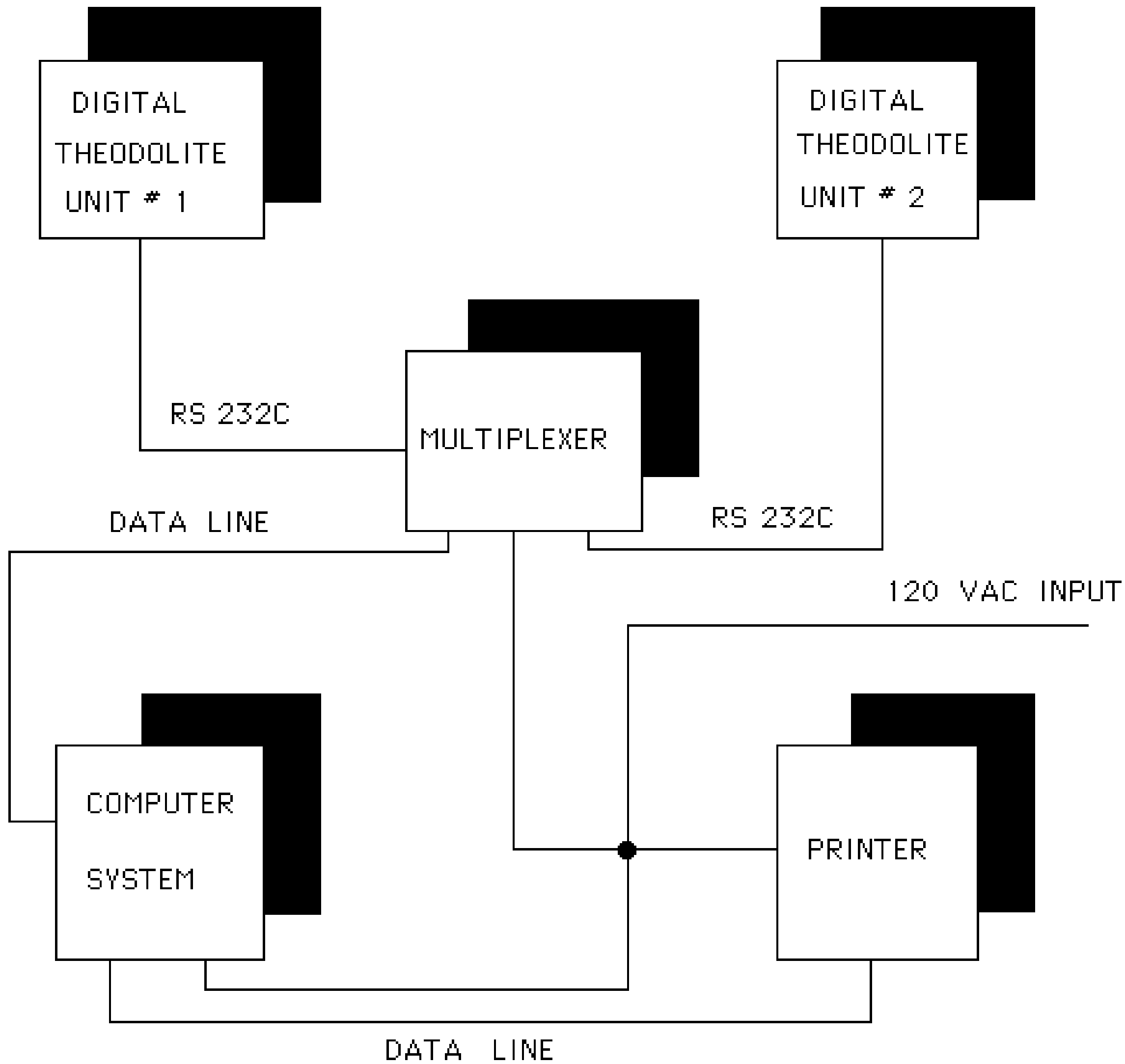

Fig. 4: Block diagram representation of the Surveying System.

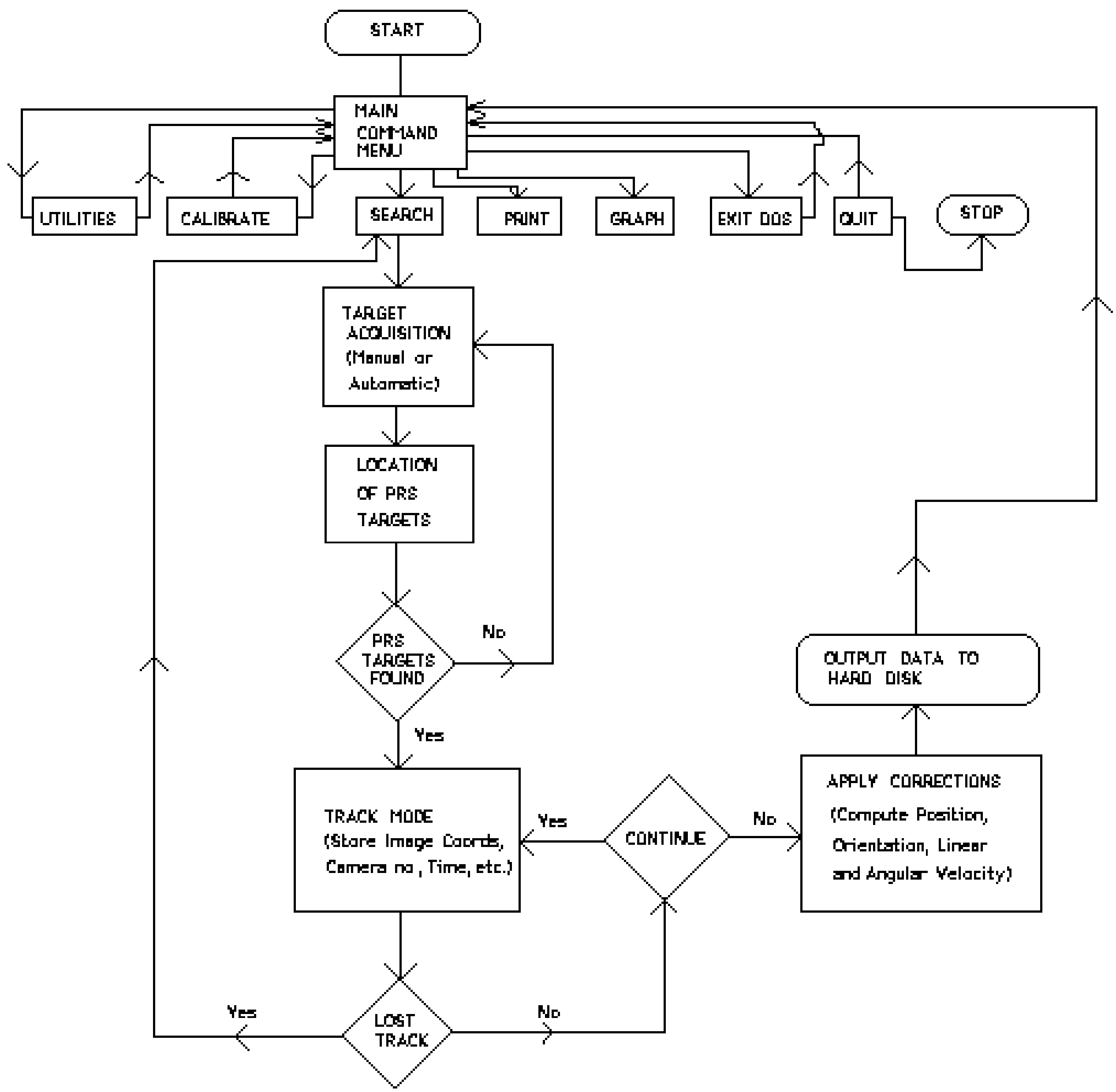

Fig. 5: Flow Chart for PRS Software Development.

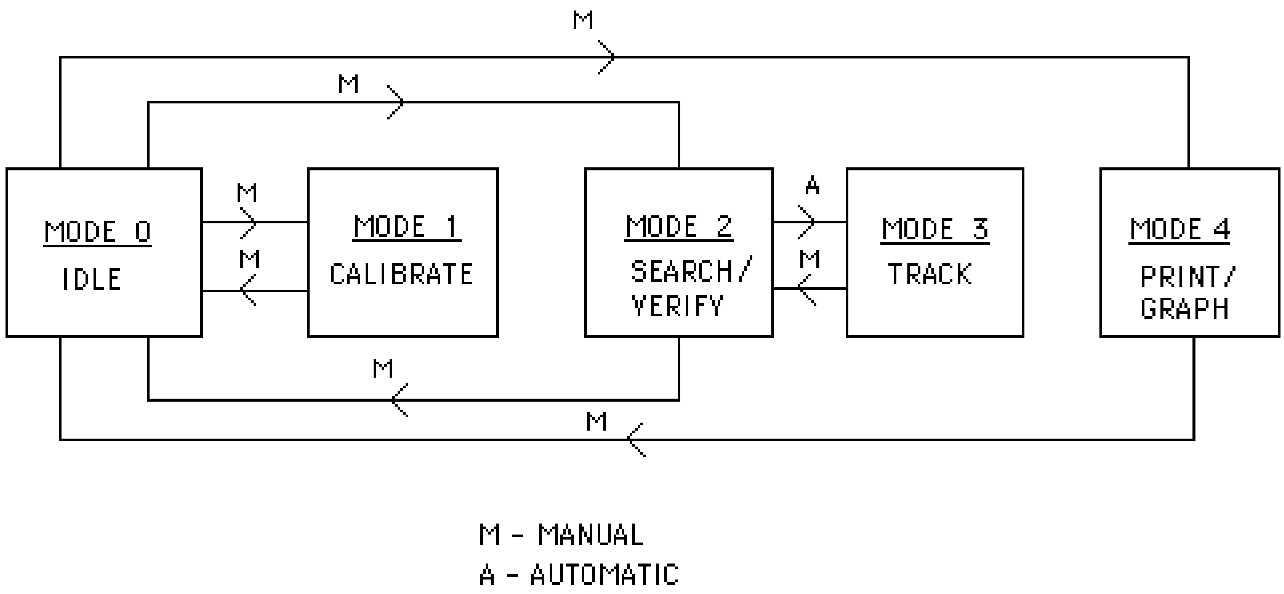

Fig. 6: Operating Modes and Transitions.

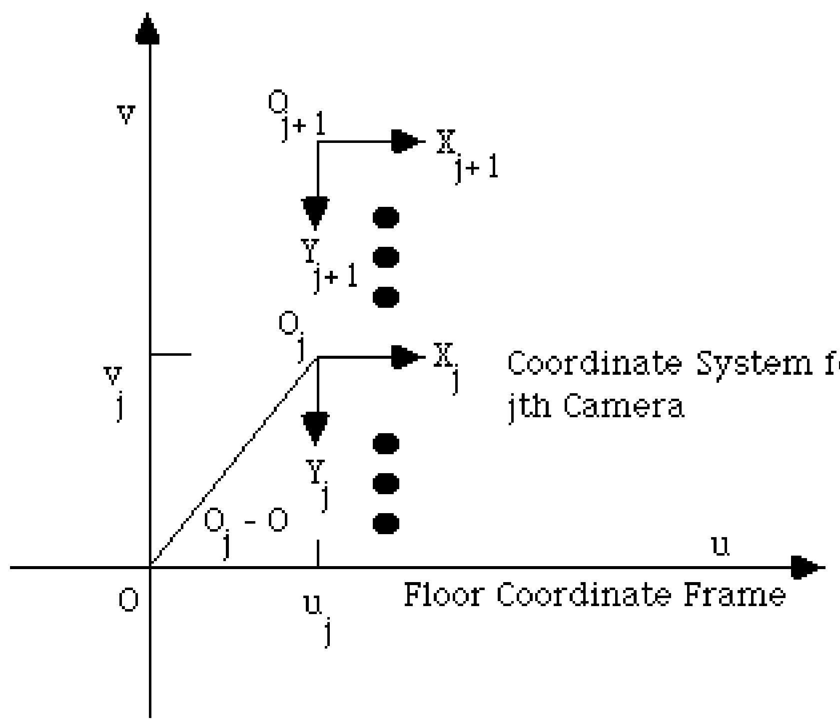

Fig. 7: Relationship between Floor Co-ordinate Frame (or the Reference System) and different Camera Co-ordinate Frames.

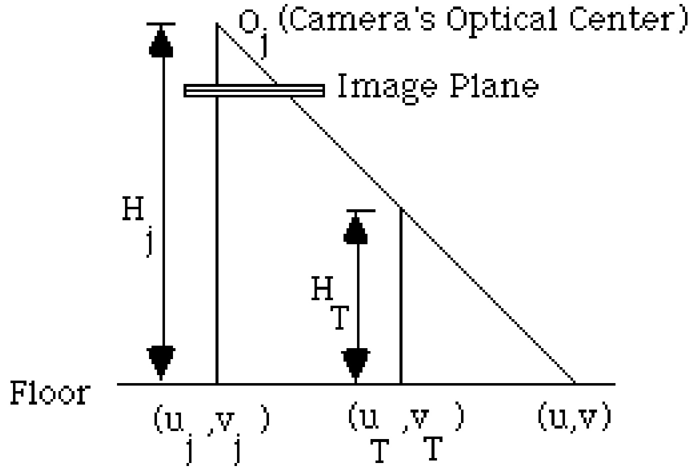

Fig. 8: Target-Height Correction Geometry (Forward Transformation).

Figs. 9 and 10 not available.