

**POSITION REFERENCE SYSTEM**

**A User's Manual**

by

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## **ABSTRACT**

This report presents documentation of (a) the Hardware Configuration, (b) the Mathematical Modeling of the Position Reference System (PRS), and (c) the Experimental Results. In the first section, various components of the PRS, with their inter-connections, are described. In the second section, algorithms and techniques to test the performance of laser tracking systems by means of cameras are discussed. 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. In the last section, various experiments will be conducted in order to find accuracies in our approach. The technical specifications of the system will be given. The print-outs as well as plots of the state vector will also be presented.

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## INTRODUCTION

The Position Reference System (PRS) is a calibration and test facility for laser tracking systems (Fig 1.1), which is being built at the Lyndon B. Johnson Space Center (JSC), NASA. The PRS is especially intended for calibrating tracking systems to be used for docking and rendezvous.

The laser tracking system will lock onto a target held by a robot. The target has corner reflectors identical to those on a vehicle which is to rendezvous with the Space Station or the Space Shuttle. The robot, controlled by a personal computer (PC) 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, the robot will be monitored by *eleven* charge-coupled device (CCD) video cameras located in the ceiling. Self-illuminated targets (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 robot's laser target. With this information, its orientation (assuming the relative positions of the PRS targets with respect to the corner reflectors are known) will be compared with that indicated by the output of the laser tracking system under test.

This report is organised into three main sections (Fig. 1.2), namely:

*Section A.* Hardware Configuration of the PRS

*Section B.* Mathematical Modeling of the PRS

*Section C.* Experimental Results

Each section will be discussed separately. In section A, all the hardware components used in the PRS laboratory will be discussed, with general descriptions of their features/applications. Their various connections to other units, in order to form a

Fig. 1.1: PRS Laboratory (not available)

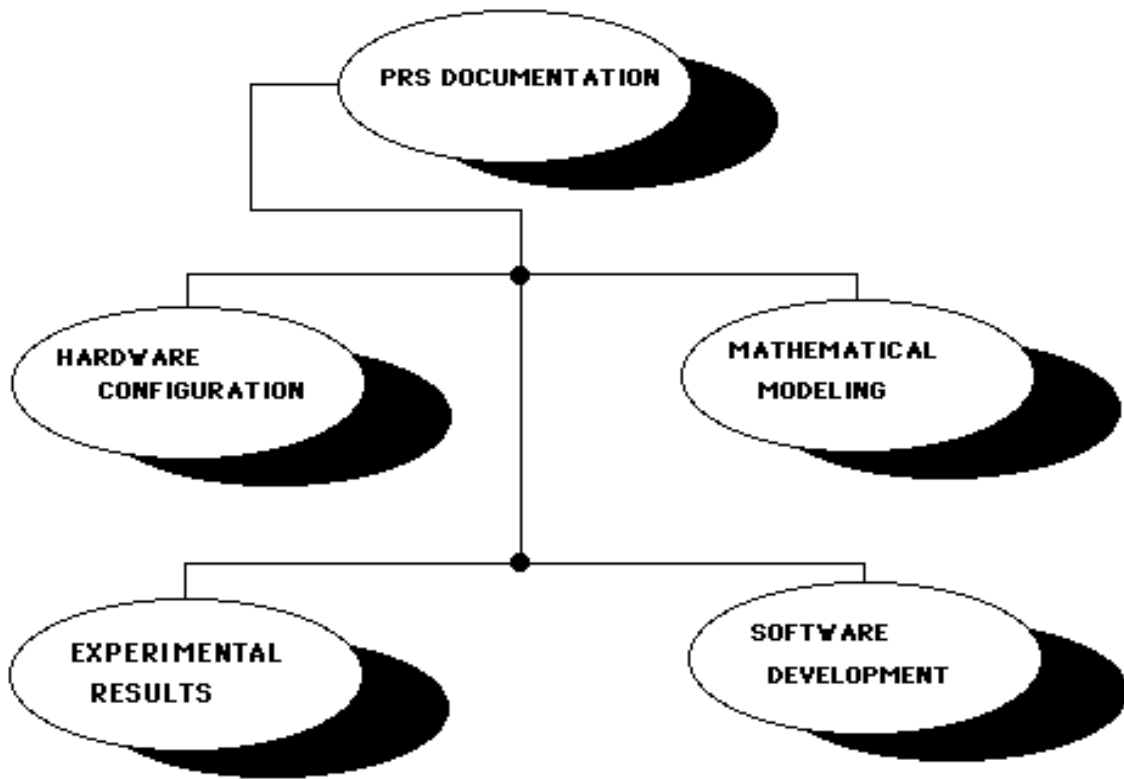


Fig. 1.2: Various components of PRS Documentation.



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complete system, will also be presented. In section B, all the algorithms will be discussed that provide a mathematical model for the PRS. Section C will present various experimental results in the form of technical specifications, accuracies, various print-outs and plots.

There are, however, separate reports on the software documentation, namely, *THE SOFTWARE DOCUMENTATION OF THE POSITION REFERENCE SYSTEM : A User's Manual* (Ver. 1.0), and *THE SOURCE CODE FOR POSITION REFERENCE SYSTEM* (Ver. 1.0) . The former gives a documentation of the routines used for PRS. The latter provides the first version of the source code for PRS.

**SECTION A**

**HARDWARE CONFIGURATION  
OF THE  
POSITION REFERENCE SYSTEM**

## HARDWARE CONFIGURATION OF THE PRS

### 2.1 OVERVIEW

This section describes various components that are used in the PRS project. The features of the hardware components are described. The various inter-connections are also discussed.

The hardware is essentially divided into three major units (Fig. 2.1):

- (I) The Tracking System
- (II) The Target Assembly and
- (III) The Surveying System .

The *Tracking System* has various components required to track a target (a robot carrying three bright lights or *PRS targets* ). Both hardware as well as software of this system will be described. The *Target Assembly* comprises the *Robot* and the *Control Unit*. The *Surveying System* is used to survey the laboratory floor in order to calibrate the CCD cameras - essential components in the PRS project. In table 2.1, we present a breakup of the three units of the hardware.

Table 2.1 : Hardware Configuration of the PRS.

<u>Tracking System</u>	<u>Target Assembly</u>	<u>Surveying System</u>
* Main Computer & Display	* Robot	* Computer System
* Frame Grabber	* Control Unit	(Computer, Printer,
* CCD Cameras & Display	(Host Computer,	Keyboard, Display)
* Video Switcher	Joystick, RF modems)	* Digital Theodolites
* Mouse		
* Printer		
* Plotter		

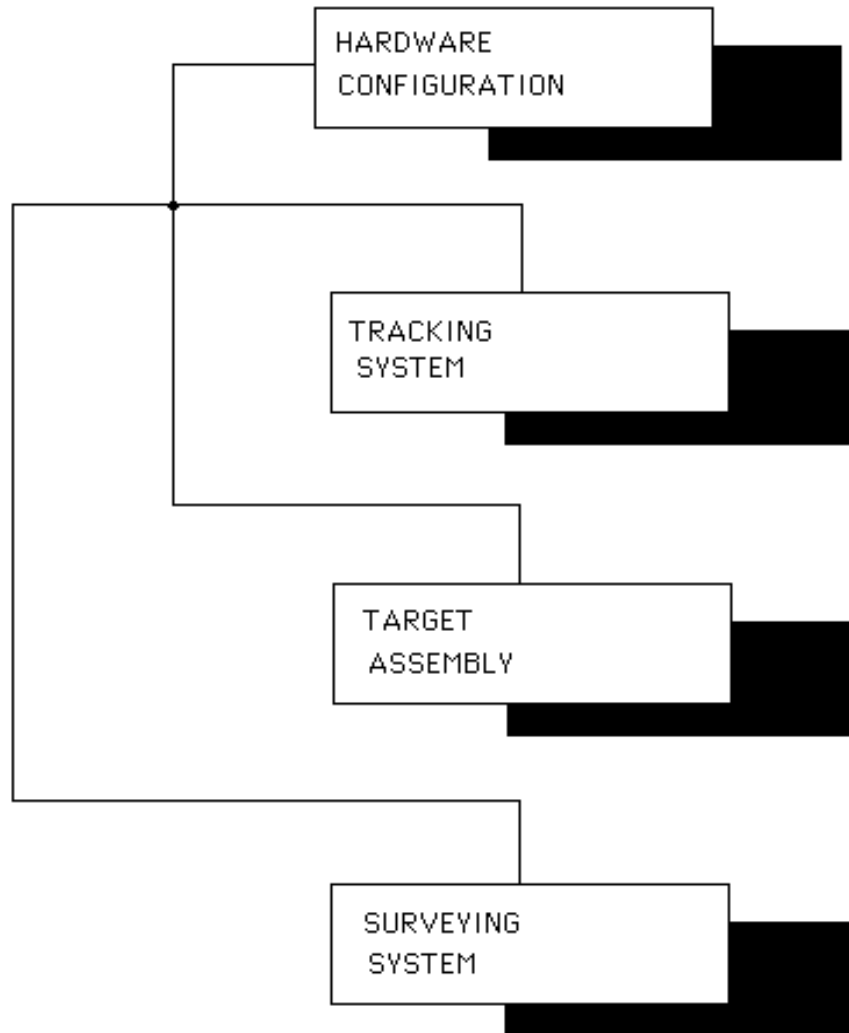


Fig. 2.1: Various components of Hardware Configuration of PRS.

## 2.2 THE TRACKING SYSTEM

The various components of the Tracking System are described in this section (Fig.2.2).

### 2.2.1 THE MAIN COMPUTER

#### General Description

The main computer used in the laboratory is the COMPAQ DESKPRO 386/20 Personal Computer (ref.[1]). It's main features are (Fig. 2.3):

- \* 20 MHz INTEL 80386 microprocessor.
- \* Cache memory controller with its own 32 Kbytes of high-speed static memory. Disk caching permits the user to hold in system memory recently-accessed data sectors reducing the number of required accesses to the fixed disk drive and thereby increasing the performance in disk-read intensive applications.
- \* System memory expandable up to 16 Mbytes without using any additional expansion slots.
- \* An industry-standard 5 1/4 -inch 1.2 megabyte diskette drive
- \* 60-megabyte fixed disk drive (half-height)
- \* 1 meg 32-bit system memory board (RAM)
- \* MS-DOS operating system version 3.31
- \* COMPAQ Enhanced Keyboard with 101 keys, and a separate numeric keypad
- \* 25-pin parallel printer interface
- \* 9-pin asynchronous communications interface
- \* real-time clock/calendar with battery
- \* Four 16-bit and two 8-bit expansion slots (one full-size, one half-size).

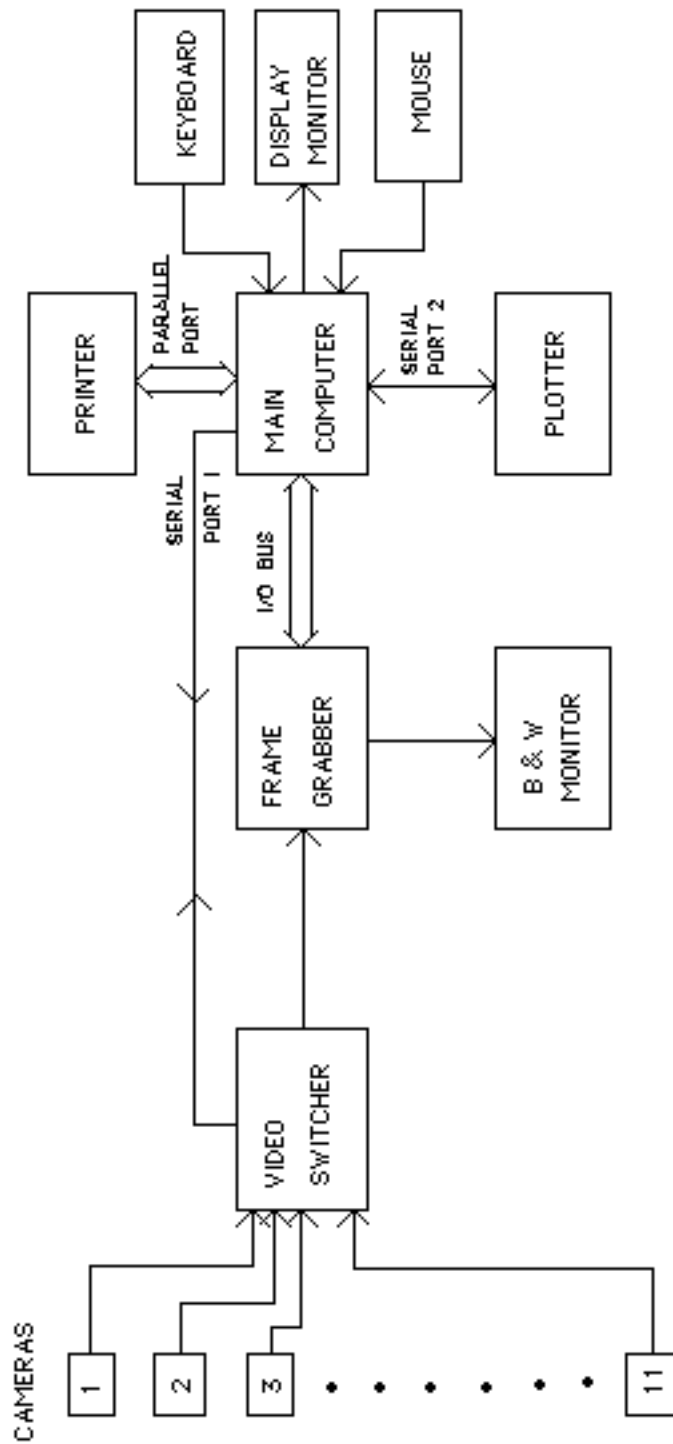


Fig. 2.2: Block diagram representation of the Tracking System.

Fig. 2.3 not available.

The options that are installed include:

(i) A video graphics controller (VGC) board (COMPAQ's PARADISE, ref.[2]). It offers outstanding performance resolution, and compatibility; generates high-resolution text and graphics in up to 256 simultaneous colors, out of a palette of 256,000 when used with any multisync monitor (NEC Multisync II in our case). Features of the VGC Board include:

- # Full IBM Video Graphics Array (VGA) hardware compatibility up to 640x480 graphics resolution
- # CGA and EGA BIOS compatible
- # up to 250 simultaneous colors in 520x200 resolution
- # performance enhancements to increase screen refresh speed
- # Functions in 8- or 16-bit expansion slots
- # standard 250 kbytes of video RAM

No jumpers should be changed when the VGC board is installed.

(ii) A 360K Floppy Disk Drive

(iii) A 20 MHz 803387 Math Co-processor used to enhance the processing power of the computer provides compatibility with the extensive library of sophisticated applications developed for 80287 coprocessors while executing floating-point-intensive operations twice as fast as an 80287 coprocessor.

(iv) 1 Meg 32-bit Memory Module: A plug-in module adds 1 megabyte of 32-bit memory to the COMPAQ 1-Megabyte 32-bit RAM

(v) Secondary communications port. The DIO-500 Multi-I/O card (ref.[3]) is used for this purpose, which provides up to two RS-232C serial interface ports and a parallel port. The 25-pin serial port is used to communicate with a plotter (HP 7550A in our case). Do not set DIP switches when this card is installed in the main computer.

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### Getting Started

Follow these steps:

Step 1: Place the system unit on a level work surface with the front facing toward the user. Do not plug in or turn on the system unit.

Step 2: After the three screws located at the rear of the system unit are removed, carefully pull the cover of the system unit straight toward the user and then lift the cover up and away from the system.

Step 3: Install the VGC board, the frame grabber (MVP-AT/NP), the primary and secondary communications ports, and the mouse card in the available slots.

Step 4: Put the system unit cover back.

Step 5: Connect the rest of the components of the Tracking System to the main computer. At the back of the system unit, the expansion slots are labeled SLOT 1 through SLOT 8. At present, the configuration listed in table 2.2 is available.

Make sure the pin numbers 5, 6, and 20 of the cable which connects the video switcher to the main computer are connected together by means of jumpers. This is done because the switcher does not have any 'handshaking' capability.

Step 6: Turn-on power.

For technical specifications, the reader is referred to [1,2,3].



Table 2.2 : The Various Connections of the Main Computer

<u>Slot No.</u>	<u>Connection</u>
SLOT 1	Empty.
SLOT 2	Secondary communications port provides connection to the plotter.
SLOT 3	Frame grabber is installed here and SLOT 4. No connection is needed here.
SLOT 4	Frame grabber provides connections to the video switcher (between Channel 0 of the frame grabber and CONTROL OUT of the video switcher) and the camera display monitor (between VIDEO OUT of the frame grabber and VIDEO IN of the camera display monitor).
SLOT 5	Secondary communications port provides connections to an optional secondary printer.
SLOT 6	Video graphics controller card provides the connection to the multisync monitor.
SLOT 7	Primary communications port provides connection to the primary printer and the video switcher (DATA I/O).
SLOT 8	Mouse Card provides connection to the mouse.

### 2.2.2 THE DISPLAY MONITOR

#### General Description

The Display Monitor, called NEC MultiSync II (ref.[4]), is used with the main computer (Fig. 2.4) and is a high resolution (800 dots (H) by 560 lines (V)) color monitor that automatically adjusts to graphics board scanning frequencies from 15.5 kHz to 35 kHz (H) and 50 Hz to 80 Hz (V). It is compatible with IBM PC, PC/XT, PC/AT, PS/2 and their compatibles. It is also compatible with the IBM Color Graphics Adapter (CGA), the IBM Enhanced Graphics Adapter (EGA), the IBM Video Graphics Array (VGA) and other IBM

Fig. 2.4: The Display Monitor for the Main Computer (not available).

compatible graphics adapters. The monitor has a 14" diagonal display and a 13" viewing area.

#### Front View

The various buttons/controls are described as follows:

- (i) POWER SWITCH is used to turn the power ON (the power LED indicator is lit) or OFF.
- (ii) BRIGHTNESS CONTROL adjusts the picture brightness of the screen.
- (iii) CONTRAST CONTROL adjusts the display to the contrast preferred by the user.
- (iv) V. POSITION CONTROL adjusts the proper vertical position of the display.
- (v) V. SIZE CONTROL adjusts the proper vertical size of the display.
- (vi) H. POSITION CONTROL adjusts the proper horizontal position of the display.
- (vii) H. POSITION CONTROL adjusts the proper horizontal size of the display.
- (viii) TEXT SWITCH controls the text mode of the monitor. When it is ON, the text will appear in the color displayed by the TEXT COLOR SWITCH.
- (ix) TEXT COLOR SWITCH is used to select the text color - green, amber or paper white - when the TEXT SWITCH is ON.

#### Rear View

The various switches are:

- (i) MANUAL SWITCH: It either selects the IBM mode when OFF - to adjust itself automatically to the scanning frequency, resolution and color requirements of the IBM compatible graphics adapter being used - or the manual mode when ON - to manually select the mode (gray/color) and the number of colors (8/16/64).
- (ii) MODE SWITCH: This switch selects either the gray scale or color with a TTL signal input.

(iii) COLOR MODE SWITCH: It uses four color configurations [8/16(NEC)/16(IBM)/64] when using non-IBM compatible graphics adapters. We need to choose 16(IBM) setting for the PRS project.

#### Connecting the Display Monitor to the Main Computer

Follow these steps:

Step I: Make sure the power to the monitor and the computer is turned off. Also, make sure the MANUAL SWITCH is OFF.

Step II: Next, connect one of the signal cable to the interface on the graphics adapter. The other end of this cable should be connected to the interface marked SIGNAL INPUT on the rear of the monitor as shown.

Step III: Connect the power cord to the monitor as shown.

For technical specifications, the reader is referred to [4].

### 2.2.3 THE FRAME GRABBER

#### General Description

The frame grabber, known as MVP-AT, is basically an Image/Vision Processor (ref.[5,6]). It is capable of performing *Area of Interest* processing, real-time ALU image operations, gives flicker-free and non-interlaced display output, and has a 32-bit plane image buffer. These features allow combining extensive text, graphics, and overlay capabilities with the most advanced real-time image processing functions available. The

board performs such image processing operations as convolutions, histograms, averaging, subtraction, and many other operations at very high speeds. The Neighborhood Processor (NP) module provides pattern matching and morphological transforms. Its various imaging applications are in the fields of medicine, science, graphic arts, inspection/quality control, security, machine vision and robotics.

#### 2.2.3.1 MVP-AT

The MVP-AT contains a number of *functional modules* that are described below (Fig.2.5):

##### Memory Module

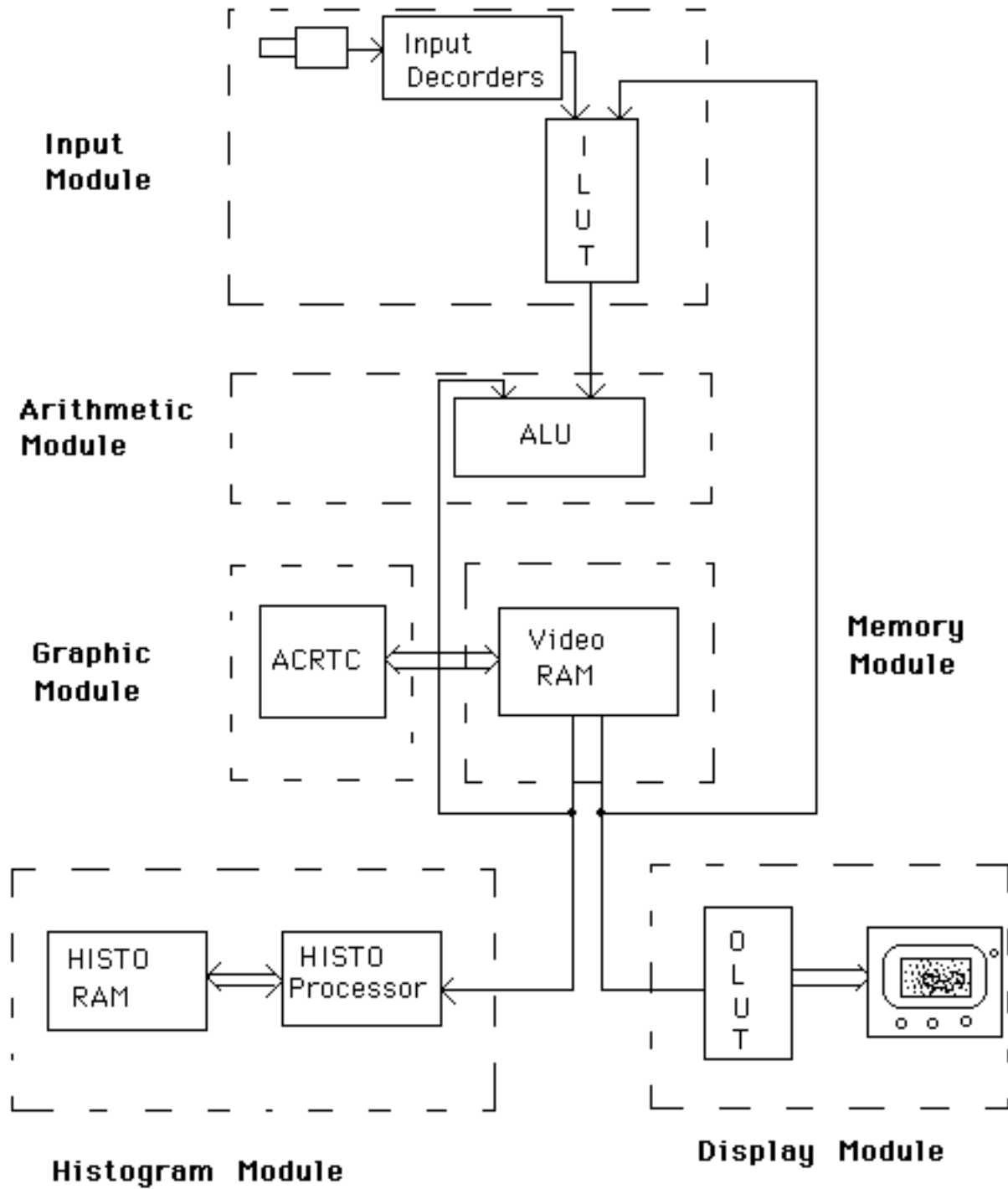
This is the central part of the system with 1 M of video memory, which is organized into four 512 x 512 x 8-bit buffers. These buffers can be organized into a variety of configurations to fit various applications, such as

- # one 512 x 512 x 24-bit buffer (color only) with or without 4-bit overlay (available for pointers, cursors, and text)
- # two 512 x 512 x 16-bit buffers
- # four 512 x 512 x 8-bit buffers with or without 4-bit overlay
- # one 1024 x 1024 x 8-bit buffer
- # two 1024 x 512 x 8-bit buffers
- # two 512 x 512 x 8-bit buffers and one 512 x 512 x 16-bit buffer

##### Graphics Module

This is composed of the Hitachi ACRTC and accesses/supports the memory module. It allows one to put computer-generated pictures, arrows and text into the frame buffers on the MVP-AT.

Fig. 2.5: Block diagram representation of MVP-AT Frame Grabber.



#### Histogram Module

It performs *intensity* and *profile* histograms. An intensity histogram is a probability function describing the gray-scale distribution of the image in a buffer. A profile histogram is an intensity sum along a predefined axis ( $0^{\circ}$ ,  $45^{\circ}$ ,  $90^{\circ}$ ,  $135^{\circ}$  on an image stored in a user-selected buffer).

#### Input Module

The input module is hardware that selects the video source, extracts video information from the source, and is user-configured through software to match the devices connected to the front-end of the MVP.

#### Display Module

This module extracts information from the memory, converts it to video and sends it to the display.

#### Arithmetic Module

This module performs all arithmetic and logical operations: on one frame buffer, between one frame buffer and a constant, or between two frame buffers.

#### 2.2.3.2 MVP-NP

The MVP-NP (*Neighborhood Processor*) offers real-time machine vision processing capabilities. It is an add-on module for the MVP-AT. It operates in binary, gray-scale and color modes and offers two major benefits: increased processing speed for neighborhood operations (e.g., convolutions); and additional processing capabilities, such as binary pattern matching and feature extraction, color classification and distance, and morphological transforms for structure/shape determination (such as intersection, union, complement, reflection, translation, dilation, and erosion).

Table 2.3 briefly compares the features of the MVP-AT with or without the neighborhood processor module. The processing speeds are given in frame times for a 512 x 480 image.

Table 2.3 : Comparison of Processing Speeds of MVP-AT and MVP-NP

<u>Feature</u>	<u>MVP-AT</u>	<u>MVP-NP</u>
Binary Pattern Matching	No	2 F.T.*
Image multiply	No	2 F.T.
Convolutions		
3 x 3	10 F.T.	2 F.T.
5 x 5	26 F.T.	8 F.T.
7 x 7	50 F.T.	12 F.T.
Color Processor	No	2 F.T./color
Erosion/Dilation	10 F.T./iteration	2 F.T./iteration
Connectivity Analysis	10 F.T./iteration	2 F.T./iteration
Line Thinning	10 F.T./iteration	2 F.T./iteration

\* F.T. = Frame Time (=1/30th of a sec)

### 2.2.3.3 Imager-AT/NP

The Imager-AT/NP software package contains a library of routines, over 150 in number, designed specifically for an IBM PC AT, or compatible, equipped with an MVP-AT/NP. Each routine can be called from the library and compiled. The Imager-AT can be used as an *interpreter*.

The routines of the Imager-AT/NP are listed in table 2.4:

Table 2.4 : Imager-AT/NP Subroutines

Convolutions

- \* N x M kernals
- \* Built-in types
  - # Roberts, Sobel
  - # Horizontal edges
  - # Vertical edges
  - # Sharpening
  - # Pixel averaging

Statistical Functions

- \* Histograms
- \* X, Y, 45<sup>o</sup> and 135<sup>o</sup> profiles
- \* Object summation
- \* Object reads
- \* Graphical display

Advanced Functions

- \* Erosion
- \* Dilation
- \* Connectivity Analysis
- \* Line thinning

Graphics

- \* Overlay onto an image
  - # Text
  - # Cursors
  - # Polygons, rectangles
  - # Circles, lines

ALU Functions

- \* Single Image
  - # Frame averaging
  - # Multiply/divide
  - # Non-linear transforms
- \* Inter Image
  - # ADD/SUB/OR/XOR
  - # XNOR/MIN/MAX

And Many More

- \* Bus transfers
- \* Windowing
- \* LUT manipulation

For technical specifications on MVP-AT/NP, the reader is referred to [5,6].



#### 2.2.4 THE CCD CAMERAS

##### General Description

CCDs are capable of sensing images, processing signals, and performing the functions of analog or digital memory. The CCD was invented by the Bell Telephone Laboratory in the U.S.A. in 1970. They have the ability to store and transfer electrical charges (ref.[7]). Through the use of these functions, the CCD solid-state image pickup device for video cameras was developed. The operating principle for CCD is *charge-coupling*. It is the process of transfer of all the mobile electric charge, called *packet*, stored within a semiconductor location, called storage element, to a similar, adjacent storage element by alternately raising and lowering voltages externally. *Area Imaging Devices* (AIDs) have an X-Y array of sense elements, and sense an area image. They are built with both vertical and horizontal transfer gates and transport registers.

The NEC TI-22PII cameras, used in the PRS laboratory, use a new CCD device as the pickup element (ref.[8,9,10]). It converts intensity information of the scene into an electrical signal. Due to the inherent properties of CCD elements, they are far superior to cameras using pickup tubes in their relative performances/applications (Fig. 2.6). The pick-up area of these cameras typically has 406 picture cells in the horizontal direction and 490 in the vertical direction for a total of 199,000 picture cells on the chip (substrate) measuring 8.8 mm wide X 6.6 mm high. There are 2 optical black cells at the front of each line and 20 at the end of each line so that the effective number of picture cells is 384(H) X 490(V). Each camera is equipped with Fujinon TV lens (Model# HF5.5A).

##### Connecting the Camera(s) to the Video Switcher

Connect the VIDEO OUTPUT of the camera(s) to the VIDEO IN of the video switcher by means of a cable.

Fig. 2.6: The CCD Camera (not available)

## 2.2.5 THE CAMERA DISPLAY MONITOR

### General Description

The monochrome monitor, built by Conrac Corporation (Model # 2600C9), is used in the project for displaying the output of each CCD camera (ref.[11]). It is an economical, highly reliable monitor designed for applications such as surveillance, industrial TV, broadcast signal viewing and alphanumeric display. Some of its features are (Fig. 2.7):

- \* 9" diagonal CRT
- \* 750 lines minimum resolution
- \* P4 phosphor standard; many other phosphors available
- \* Wide range of scan frequencies; up to 34 kHz
- \* 12, 25 or 30 MHz video bandwidths
- \* 50 flux brightness

### Connecting the Camera Display Monitor to the Main Computer

Connect the monitor to the main computer with a cable between VIDEO IN of the monitor and VIDEO OUT of the frame grabber, which resides in SLOT 4 of the main computer.

Fig. 2.7: The Camera Display Monitor (not available).

## 2.2.6 THE VIDEO SWITCHER

### General Description

The video switcher used in the PRS laboratory is called COAXSELECT™ (Fig. 2.8). It is a micro-processor-controlled remote video-switching system and is designed for use with coaxial cable-controlled camera control systems (ref.[12]). The COAXSELECT switcher receivers can be controlled by a computer and can communicate with the switcher transmitter by use of the built-in RS232C-compatible serial data link. The basic switcher can control, switch and sequence up to 16 camera inputs (expandable to 32 camera inputs).

### Installation

Connect the coaxial cable from each camera to a video input on the back of the RS850/RS1650/RS3250 switcher receiver. All the video inputs and outputs should be terminated in a single 75 ohms resistor at the extreme end of the line only. Failure to do so will result in improper switcher operation. Video level from each camera should be adjusted to approximately 1 volt. Also, connect the CONTROL OUT to channel 0 of the frame grabber in SLOT 4 of the main computer.

### System Operation

Cameras are selected by putting the function switch in the control position (down) on normal transmitters. The channel indicator will light steady in case of a normal operation. If the switcher does not switch and the indicator starts to flash, the channel has been *locked* by a camera control transmitter and no operation is possible until the lock has been removed.

Fig. 2.8: The Video Switcher (not available).

#### Operation on Serial Data Input

The switcher has the capability of being operated over an RS232C data link either by a computer or terminal or by a COAXSELECT transmitter. If a computer or terminal is connected directly to the data input of the switcher receiver, no transmitter is required in the system. Character format for video switching is S1, S2, ... , S31, S32, etc. All commands must be followed by a carriage return. Available baud rates are selectable by the first two Dual In-line Package (DIP) switches on the control card (left side). In our application, 1200 baud rate is used (SW1 = On and SW2 = Off).

### 2.2.7 THE MOUSE

#### General Description

The mouse (Fig. 2.9) is a hand-held pointing device that enables one to use computer with greater ease and efficiency (ref. [13]). It provides speed, accuracy, and simplicity in one's work environment, and is compatible with almost all PCs (IBM PC, AT, PS/2 and 100% compatibles, Compaq computers, etc.). Its hardware and software support almost all displays (IBM Monochrome, Color, Enhanced Color, and Personal System/2 Displays, and 100% compatibles), and display adapters (IBM Monochrome, CGA, EGA, PS/2 Display adapters, Hercules Graphics Card, and 100% compatibles).

#### Getting Started

In order for the mouse to operate normally, the hardware as well as software need to be installed on the system.

Fig. 2.9: The mouse and its installation (not available).

### Setting Up Mouse Hardware

For the PRS project, we are using the *Bus Interface* for the mouse that consists of a printed circuit board which is to be installed in an available expansion slot in the computer. The Bus Interface is equipped with three jumpers; labeled J2, J3, J4; that must be set so that the mouse functions properly with the type of computer, interfaces, and peripherals we are using. Each jumper consists of a plastic block and a small, removable clip that fits over a pair of pins on the block to specify the jumper setting.

If the Bus Interface is installed in slot 8 of an IBM PC/XT (slot farthest to the right when facing the front of the system unit), we need to change the setting of the jumper labeled J2 by placing the jumper clip to cover the top two pins on the jumper (XT slot 8, as indicated on the Bus Interface). The default setting of the clip is, otherwise, on NORMAL.

The Bus Interface for the Mouse uses the *InPort Device Interface*, a pointing device interface that consists of a custom chip and a 9-pin circular connector. The mouse uses this 9-pin circular connector that plugs into the InPort Device Interface connector on the printed circuit board. Jumper labeled J3 is preset to indicate that the Bus Interface is the *primary* InPort Device Interface.

The third jumper, labeled J4 and known as *Interrupt jumper*, provides various interrupts, which are temporary breaks in the sequence of a program caused by a various I/O devices such as keyboards, drawing devices, and printers. We must specify a mouse interrupt that does not interfere with other devices, as no two devices connected to the same computer can use the same interrupt level. The jumper labeled J4 has pin pairs labeled 2,3,4, and 5. For our applications, we use pin pair 5 settings.

### Connecting the Mouse

Follow these steps:

Step 1: Turn off the computer.

Step 2: Locate the 9-pin circular port on one of the adapters installed in the computer. It should correspond to the 9-pin connector of the Mousecable as shown in Fig. 2.9 .

Step 3: Attach the Mousecable to the InPort Device Interface connector.

#### Setting Up Mouse Software

Before we install software, we should make a copy of each disk. For this process, we need a DOS disk, version 2.0 or later. The *Setup disk* is the first disk to use after the mouse hardware is installed.

A program called *msetup* is included on the Setup disk which enables one to install the software the Mouse needs in order to work with the computer. This program copies the *mouse driver* - the file that enables the Mouse hardware to work with the computer, and the software we need to load the mouse - to either the hard disk or to a floppy disk. To run

*msetup* :

Step 1: Start DOS.

Step 2: Insert the Setup disk into drive A.

Step 3: At the DOS prompt, type

*a: msetup*

and hit <RETURN>.

It is extremely easy to follow the on-screen instructions if the operator knows the

type of computer, display, and the peripherals being used. The name of the mouse driver should be added to the search path in the *AUTOEXEC.BAT* file so that one can easily access the mouse driver later.

## 2.2.8 THE PRINTER

### General Description

The printer used for our project is Epson FX-286 (ref.[14]). It has a fast print speed (160 characters per second), improved throughput for rapid processing of documents, and 2K print buffer for smooth operation. It has the ability to select various features (*Emphasized* and *Expanded* printing) and several different print modes (Roman and *Italic* fonts, two kinds of **Bold** printing).

The printer assembly has various parts (Fig. 2.10), which are: the printer, a manual-feed knob, a paper separator, two protective covers, one ribbon cartridge, a tractor unit, and a dust cover for the tractor unit. For continuous-feed operations, enough room must be allowed for the paper to flow freely by mounting the printer on a printer stand. The computer communicates to the printer through a parallel interface, labeled *LPT1*, by using the Centronix standard parallel interface scheme.

### Starting Up

Follow these steps:

Step 1: First make sure the power switch is off. Connect the printer end of the printer cable to the connector at the right-rear of the printer.

Step 2: Load the paper.

Fig. 2.10: The Main Printer (not available).

Step 3: Turn the printer on with the toggle switch near the left-rear corner. The print head moves a little and three lights on the control panel go on. These lights are: the POWER light, the READY light, and the ON LINE light. If the ON LINE and READY lights are not on, push the button marked ON LINE. If the PAPER OUT light is on, the paper is not loaded correctly. The other buttons on the control panel are LF (line feed) and FF (form feed). The ON LINE button turns the printer on- and off-line, when the light is on and off respectively. To use LF and FF buttons, the printer should be off-line. Pressing LF produces one line feed per stroke. If the FF button is struck once, the paper advances by one computer page (form).

For technical specifications, the reader is referred to [14].

## 2.2.9 THE PLOTTER

### General Description

The type of plotter used for the PRS project is the Hewlett-Packard's HP 7550 Plotter (ref.[15,16]). This plotter is equipped with an Hewlett-Packard *Interface Bus* (HP-IB) and two RS-232-C/CCITT V.24 interface ports (Fig. 2.11). Both interfaces use the Hewlett-Packard *Graphics Language* (HP-GL) for control of plotter graphics capabilities. This section will briefly describe the HP 7550's controls and their functions.

The Cartesian co-ordinate system is used to plot. The (X,Y) co-ordinates are specified as parameters in any HP-GL instruction so that the plotter knows where and what to plot. One can express the co-ordinates with two types of units, called *plotter units* (integers) and *user units*. Plotter units are a constant, fixed size, and are the units that the plotter always uses internally - unless defined by the user to suit his/her own requirements/needs. In that case, it is a user unit. A plotter unit is equal to 0.025 mm in



Fig. 2.11: The Main Plotter (not available).

length (40 plotter units = 1mm).

#### Front Panel

The controls on the front panel are divided into three areas: the keys surrounding the display; the numbered keys; and the five cursor keys in the lower-right corner of the front-panel control area. The description for each key follows:

AUTO FEED - This key is used to select the method of feeding media into the plotter.

LOAD/UNLOAD - This key is used to load sheets from the media loading tray when in automatic feed mode, and to load and unload media manually.

NEXT DISPLAY - This key is used to get the next display of front-panel options.

ENTER - This is used to implement a new state or enter numerical input.

DISPLAY - The display indicates which display the plotter is in, displays error messages, displays operation messages, and asks for input.

PEN SELECT - If one of the keys numbered 1-8 is pressed, the plotter stores its current pen and selects the correspondingly numbered pen from the carousel.

*Cursor Keys* : These keys are used to move the pen, within the plotting limits, in the direction of the arrows.

#### Rear Panel

The rear panel provides various connections/sockets in order to connect the plotter to various equipments. There are three *interface connectors* : one labeled HP-IB, and two

RS-232-C/CCITT V.24 connectors labeled COMPUTER/MODEM and TERMINAL. The rocker switch on the right side, when facing the rear of the plotter, turns the plotter *on* and *off*.

### Operating the Plotter

Perform the following steps:

Step 1: Unplug the computer cord. Remove the cover from the main computer's system unit. Insert the Asynchronous Communications Adapter (RS-232-C interface card) in any unused slot and replace the cover.

Step 2: Make sure all power switches are in the OFF position. Connect the plotter to the main computer; by attaching one end of the cable to the secondary communications port exposed on the rear of the computer (marked SLOT 2), and the other end to the COMPUTER/MODEM connector on back of the plotter.

Step 3: The accessories available for the plotter include four *pen carousels*, four types of *pens* (paper, transparency, roller-ball, and drafting), and five types of *media* (chart paper, glossy presentation paper, overhead transparency film, vellum, and double-matte polyester film).

Select the pen type and pen colors to be loaded into each position of the carousel (paper pen with chart paper). Any number of pen positions can be used. Set the carousel over the spindle in the plotter. It will seat during the initialization sequence. After the cover is lowered and the ENTER key pressed, the carousel will make one revolution and return pen to the starting position. To remove the carousel, lift it straight up.

Step 4: Turn the plotter on and load the carousel. The plotter will initialize by rotating the carousel. During this process, the plotter identifies the carousel type and the location

of the pens in the carousel, and sets the default values for pen force and speed. At this moment, the display will read : LOAD PAPER TO PLOT, since no paper has been loaded.

Step 5: Put paper (letter or legal size, each having a different tray) in the tray, and put the tray in position. Press AUTO FEED key first and then LOAD/UNLOAD key to feed paper automatically. We are now ready to plot.

## 2.3 THE TARGET ASSEMBLY

### General Description

In this section, we present the hardware configurations and the associated software for the *Robot* and the *Control Unit*, that monitors the robot. Typical configuration of the whole setup is shown in Fig.2.12. A Cybermation *host computer* (HC-01), which is Fujitsu Micro 16s, is connected to a *joy-stick/link arbitrator box* (JA-01) through a 9600 baud serial port. The output of the JA-01 DATA LINK is in turn connected to a *radio modem* (FDX-1) 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 (Fig.2.13). 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 K2A computer.

First, we shall discuss the robot, then its control unit will be described.

### 2.3.1 THE ROBOT

The robot used in the PRS laboratory (K2A), used in its present form has three different

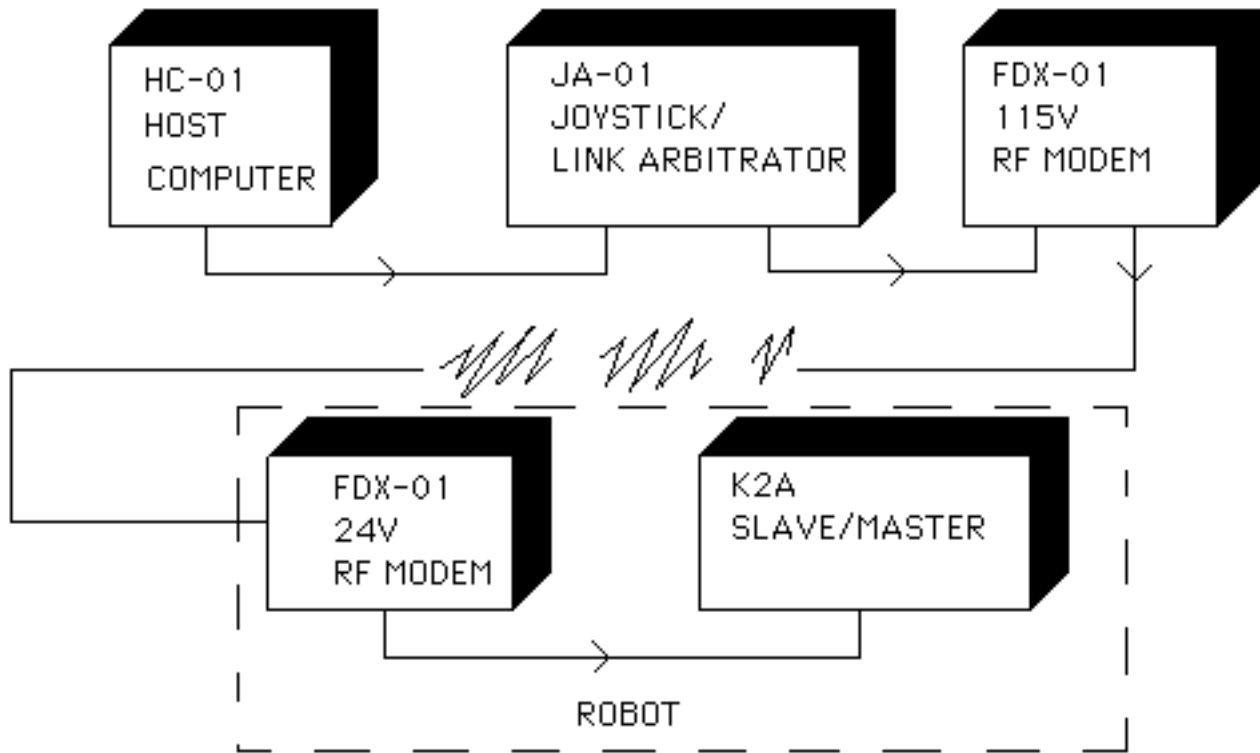


Fig. 2.12: Block diagram representation of the Target Assembly.

Fig. 2.13: Various components of the Target Assembly (not available).

sections (ref.[17]): the *lowermost section* comprising an assembly of wheels; the *middle section*, or the *platform*, which houses most of the electronics and mechanical components; and the *uppermost portion*, which comprises a TV camera, an ultrasonic mapping unit, a Laser rangefinder, an RF antenna and an FDX-1 modem assembly (Fig.2.14).

### General Description

The K2A has two motors to *steer* and *drive*, and associated power trains. The steering motor drives the vertical shaft through a spiral reducer. An optical angular pulse encoder is located on the vertical steering shaft. The drive motor too has an optical pulse encoder mounted on top of it.

All the wheels of the robot are locked together, so when the robot executes a turn, all three wheels turn in unison, and trace parallel paths to each other. The platform does not rotate, but the turret flange, provided at the top of the robot, rotates in unison with the wheels. Systems mounted to this flange will, therefore, face in the direction of the motion.

The K2A contains two electronic assemblies, the computer and the motor power amplifier. The computer is based on the Z-80 CPU. The card is powered by a chopper power supply for efficiency.

The K2A platform contains two 4-quadrant amplifiers. These amplifiers use power FET's in its H-bridges. As heavier loads are placed on the K2A, an increasing coupling occurs between the steering and the drive. This coupling is due to a increased frictional torque at the point of contact of the tire and it results in degrading the accuracy of the position determination. The use of the 4-quadrant amplifier on the drive eliminates this effect. The panel LEDs/opto-isolator signals, described in table 2.5, are required for the

Fig. 2.14: The Robot and the panel LEDs (not available).  
 amplifier and run from the computer to the motor power amplifier.

Table 2.5: Panel LEDs

<u>Name</u>	<u>Signal Description</u>
Drive PWM	Drive pulse width modulation (power) commands. Lights brighter with increasing drive command.
FORWARD/REV	This signal is used for 4-quadrant amplifiers to control the direction of the drive motor.
ENABLE	This signal must be toggled by the control computer in order to assure that a failure of the control computer will halt the vehicle in a safe manner.
STEER PWM	Steering pulse width modulation command. Lights brighter for an increasing steering power command.
LEFT/RIGHT	Steering direction command.

The robot uses two Yuasa 12 V, 65A batteries. These batteries need to be charged overnight, at a rate of 18A, after the robot is operated for 6 to 7 hours. This is done by a battery charger, BC-01 (Fig. 2.15) which supplies filtered DC. It provides opto-isolated output signals that indicate the state of charging to the robot. It may be left connected to the robot indefinitely without harming the batteries.

For our application, four high-intensity miniature light bulbs (the PRS targets) are mounted on two parallel bars, which are attached to the robot. These lights fit in cone-shaped reflectors, so that all the light emanating from these bulbs are sent in vertical direction and are easier to find in the video. A dark background is provided by keeping a card-board behind the bulbs painted flat black. Only three of the four bulbs

Fig. 2.15: The Battery Charger (not available).

are turned *on*, with a separate power supply (about 2 volts), so that they appear in a right-angled triangular fashion. This setup later makes the search of the lights in the video (and their verification) easier before they are tracked.

### 2.3.2 THE CONTROL UNIT

The control section comprises the host computer (HC-01), another set of FDX-1 RF modem, and a joystick/link arbitrator (JA-01).

#### 2.3.2.1 The Host Computer

The host computer (HC-01) for this system is Fujitsu Micro 16s™ (ref.[18]). It has various features, such as its ability to work with a number of CPUs, the speed of display operations, the quality, and the speed. It is a multiprocessor system with 8086 main processor, an auxiliary Z-80 master processor, a 6809 video subsystem processor, a 68000 CPU, and a 4-bit keyboard processor, with multi-tasking capabilities (Fig.2.16). Separate memory fields are used for character data and graphics in the video subsystem, the resolution of the graphics being 200 by 640 pixels. One can run PCDOS, CP/M86, and CP/M80 programs on this computer.

#### The System Unit

In this section, the reader will be familiarized with various switches, connections, and cables, that form the host computer and the rest of the hardware a complete system (Fig.2.17).

#### The Front Panel

The *system unit* is the main hardware unit of the HC-01, which houses three microprocessors, the RAM and ROM memories, the interfaces to other hardware units,

Fig. 2.16: The Host Computer (not available).

Fig. 2.17: The System Unit of the Host Computer (not available).

the power supply, and two disk drives. Disk drives are used to read/write information to/from floppy diskettes. One should turn on the power to the system unit, which is indicated by one of the extreme left of the three red lights on the front panel of the system unit, before inserting diskettes into the disk drives. The power switch and the reset button are located on the right side of the unit. The small red light in the lower-left corner of each disk drive will be on whenever the disk drives are reading/writing information to/from the diskettes. Looking under the front panel, we find DIP switches, which are set to the required positions when all hardware units are connected.

#### The Rear Panel

The rear panel of the system unit contains the sockets for connecting the rest of the hardware units to it. The various connections are listed in table 2.6:

Table 2.6:Rear Panel Connections

AC IN	This is where we plug in the system unit's power cord.
AC OUT	We plug the power cord from the video monitor into this socket.
KEYBOARD	The cable from the keyboard is plugged into this socket.
LIGHT PEN	The Micro 16s Light Pen is plugged into this socket.
A/D	This is the connection to the four-channel A/D convertor.
GREEN CRT	The video cable from the green-screen video monitor is plugged into this socket.
COLOR CRT	The video cable for a color video monitor is plugged into this socket.
PRINTER	This socket is for a parallel printer using the Centronics standard.
RS232C	This socket is for RS232C serial communications.



### Keyboard

The HC-01 has a 98-key keyboard. Besides the standard typewriter keys, there are ten programmable function keys, a numeric keypad, and several-purpose keys.

The keys along the top row are called *program function keys*, labeled PF1 through PF10. Each key can be programmed to enter one or more commands for CP/M-86 and Wordstar.

### Video Monitor

The HC-01 is equipped with a color monitor. The monitor can display eight colors, viz., red, blue, green, yellow, light blue, orange, white, and black. There are two switches on the front of the monitor (Fig. 2.18), one for switching the power ON and OFF, the other controls the overall brightness of the screen. A power cord is attached to the back of the monitor. There is a rectangular socket labeled RGB IN.

### Connecting the System Components

Only those connections will be discussed which are used in the PRS project.

Step 1: The system unit has the power cord, one end of which has a standard three-prong plug and should be pushed into the AC IN socket. Plug the other end of the power cable into the wall outlet before turning on the power to the system unit.

Step 2: The keyboard has one cable, one end of which is permanently attached to the keyboard. The other end fits into the KEYBOARD socket at the rear of the system unit. Place the keyboard in front of the system unit.

Fig. 2.18: The Monitor for the Host Computer (not available).

Step 3: One should check the DIP switches on the front panel of the system unit, before connecting the monitor. Get the video cable and notice it has one end that has a large rectangular connector and the other end has the same type of connector as of the keyboard. Plug the large connector into the RGB IN socket at the back of the monitor. The other connector fits into the RGB CRT socket at the back of the system unit. Plug the power cord into the AC OUT socket at the rear of the system unit, and turn the power switch to the ON position.

#### 2.3.2.2 The FDX-1 RF Modem

This modem (ref.[17]) is widely used for remote control applications by radio (Fig.2.19). In our project, it links the robot to the host computer remotely, so that the robot could be driven either manually or automatically, and be under the supervision of the operator continuously. ASCII communications between the FDX-1 and local data sources is done at a higher baud rate (9600) than the link can carry. A buffer is provided that absorbs bursts of this data to feed them to the encoder at a lower rate. The ASCII Interface to the RDX-1 is at standard 25 Pin female "D" connector with connections as shown in Table . The ASCII format is set to 8 data bits/no parity/2 stop bits.

The transmitting section of the FDX-1 converts the ASCII format, by means of the Harris HD-3-15531B chip, to a Manchester bi-phase code for transmission at slightly greater than 2400 Hz.

The FDX-1 is equipped with a 450-470 MHz FM receiver-transmitter pair with a 2 watt power output. The pair is connected to an antenna. Communications interruptions may occur due to radio interference, or as a result of the signal being shifted in phase and thus concealing the main signal. These can be avoided by either relocating the base FDX-1 antenna, or use a YAGI antenna on it (50 ohm).

Fig. 2.19: The RF Modem of the Control Unit (not available).

### 2.3.2.3 The Joystick Interface/Link Arbitrator

The JA-01 is connected to the HC-01 through its serial port marked HOST A (ref.[17]). The serial port marked DATA LINK is connected to the FDX-1 RF modem to control the K2A (Fig. 2.20). The JA-01 has a few operator controls, that include a RESET button, three LED's, 7 special function keys, and the Joystick.

The JA-01 passes characters (P, Q, R, S) from the host input to the serial data link output, and data from the link input to the host output. All communications are in the form of 8 bit/no parity/two stop bit characters. It interfaces the hosts and the link at a fast data rate (9600 baud).

### 2.3.3 STARTING THE SYSTEM (HC-01 AND K2A)

To boot up the system, follow the following steps:

Step 1: Turn on the AC power (on right side rear of HC-01).

Step 2: Insert the CP/M-86 diskette into Drive A (left-hand drive) and press the reset button. This procedure loads the operating system into memory. When it is done, the red light on Drive A will go out. On the monitor screen, we will see the *CP/M-86 copywrite notices* as shown in table 2.7:

Table 2.7: CP/M-86 Copyright Notices  
CP/M-86 Ver. 1.1 Serial Number 925-9129  
copyright (c)1982 by DIGITAL RESEARCH  
Fujitsu Micro 16s BIOS Ver. 3.0 copyright (c) 1983  
System generated 9 June 1983  
Memory Capacity = 128 KB

Fig. 2.20: The Joystick/Link Arbitrator (not available).

Step 3: Place the K2SRV Operating Disk in Drive A and shut the drive door.

Step 4: Press the reset button (right side, front).

Step 5: When the system has signed on and given a prompt, enter

```
A> K2
```

and hit <RETURN>.

*K2SRV.COM* is an application program, which runs on the HC-01, written to monitor and control the robot. It incorporates the Cybermation *Real Time Menus* (RTM) Table Compiler. RTM has been used to solve several control problems. K2SRV provides the operator with a high speed visual indication of the status of the robot, the communications link, the JA-01, and the HC-01. It is actually composed of several sub-programs assembled using the M-80 Assembler and linked using the L-80 Linker. *K2SRV* loads and fills in the screen with menus. The HC-01 has ten special function keys marked <PF1> to <PF10>. These keys represent different system commands. For our application, we are interested in function of only two keys, <PF6> and <PF10>.

<PF6>: *Select Manual/Teach Mode (Forward)*

In this mode, the robot is driven manually from the joystick of the JA-01. The HC-01 requests the A/D readings for the X and Y co-ordinates of the outputs of the JA-01, transmits these values directly to the K2A so as to control the drive and steering motors.

<PF10 >: *Halt or Emergency Stop*

This command causes the system to send continuous halt sequences to the K2A.

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Step 6: Turn on the platform power to the K2A with the key switch (assuming the K2A is fully charged up and ready to go). Turn on power to the PRS targets (three only).

Step 7: Turn on the sensor system power with the toggle switch located between the halves of the turret assembly. The camera will rotate counter-clockwise to the stop and return to the home position. The ultrasonic mapping unit will begin scanning. With a charged battery installed in its bracket, the Laser rangefinder may be turned on.

Step 8: Turn on the CCD cameras and the RF link assembly (FDX-1 and JA-01).

Step 9: Hit <PF6> key to get into Manual/Teach mode. We are ready to monitor the K2A. In case of an emergency, hit <PF10> key, or turn off the HC-01. The K2A can be stopped either by shutting off the power supply to it, or by simply by pressing one of the red buttons around its lowermost portion of its body (labeled *EMERGENCY*).

### Messages

These are various messages displayed on the screen in the form of strings. If there is an abnormal condition, a flashing message with a beep to catch the operator's attention will be displayed. The reader is referred to [ ] for details on these messages. Here we shall present a few of them which we usually come across while working with the K2A.

#### System Status Messages

NORMAL MONITORING: System is operating normally.

INTERRUPT FAILURE: Self diagnostic message indicating a interrupt hardware failure in HC-01.

SUPER LINK FAILURE: Communications to the robot has been interrupted.

JOYSTICK FAILURE: The JA-01 does not respond to interrogation.

#### Robot Status Messages

ALL SYSTEMS NORMAL: Robot status is normal.

DRIVE SERVO LIMIT: The drive servo is at full power. In manual modes, this is only a warning.

STEER SERVO LIMIT: Same as above but for the steering servo.

## 2.4 THE SURVEYING SYSTEM

### General Description

The Surveying System is a *Real Time Measuring* (RTM) 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 (Fig.2.21). This system comprises the AIMS II Computer System, with an IBM Personal System/2 Model 30 Computer, an OKIDATA Microline 182 Printer, an IBM Personal System/2 Display (monochrome), and a Keyboard; the two high-precision KIT-2 Digital Theodolites; and AIMS II Software Package.

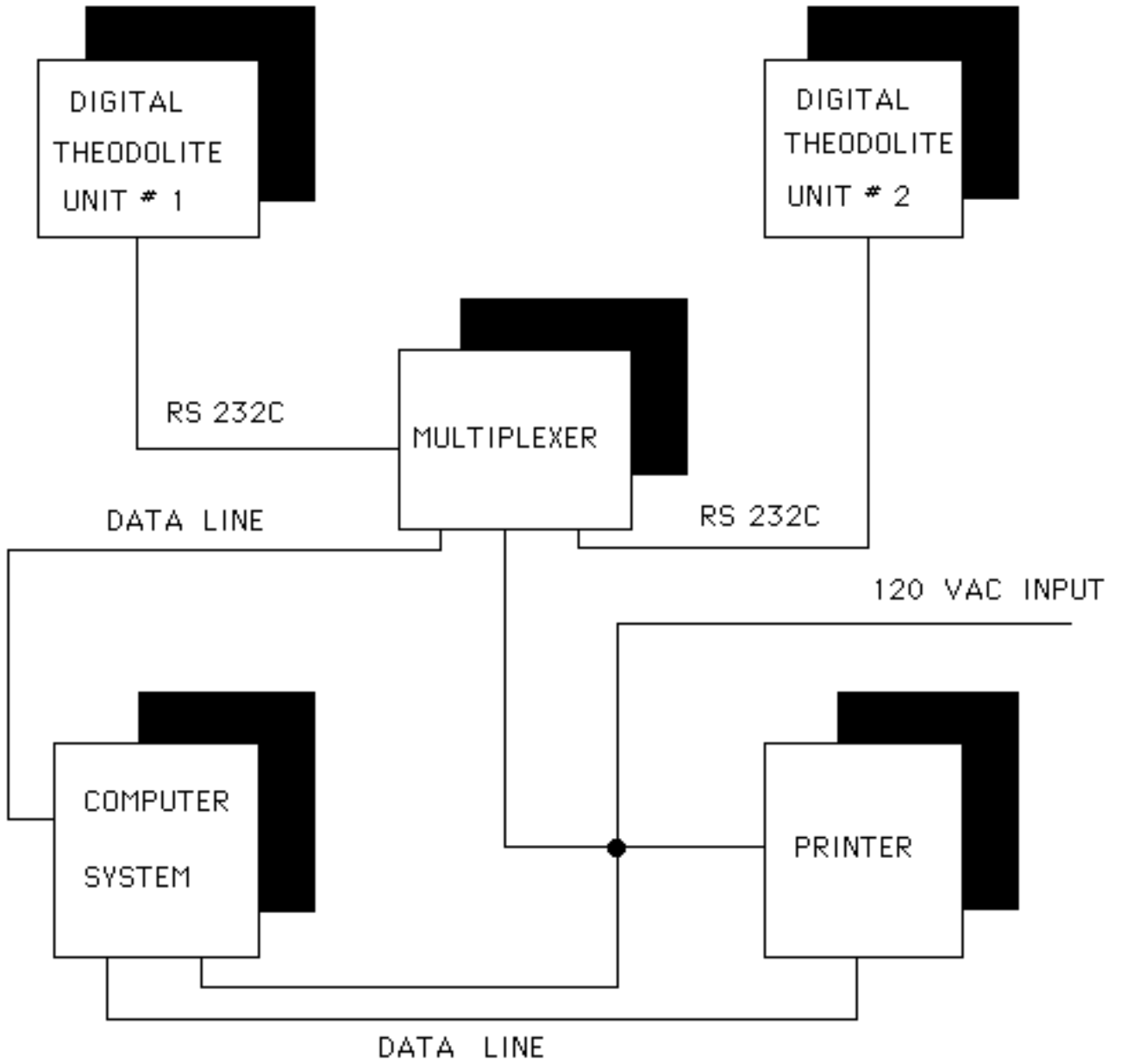


Fig. 2.21: Block diagram representation of the Surveying System.

The theodolites are used with the computer system to measure; to record azimuth and elevation angles from the digital theodolites to the target, and from the distance between the last two observed targets, in order to establish any user-defined XYZ co-ordinate system, or a reference system. The determination of the co-ordinates of spatial points relative to this reference system is based on the principle of vector analysis (3-D triangulation).

The hardware details, along with the installation procedures, of the system components are described as follows:

#### 2.4.1 THE AIMS II COMPUTER SYSTEM

The components of the Computer System are the IBM PS/2 Model 30 computer, IBM PS/2 monochrome monitor, a keyboard, and Okidata ML 182 printer (ref.[19,20,21]). The computer contains the CPU, 640 kB RAM, power supply, 20 MB hard-disk, I/O connectors and interface circuitry. The keyboard is a standard typewriter configuration with easy entry of numeric data, and an editing keypad containing many of the commonly used editing functions (expandable to 36 functions by using the combination of shift and control keys). The display is used for communication between the operator and the computer by entering data from the keyboard. The display shows 20 lines of 80 characters. The printer is a dot matrix serial printer with an input buffer capacity of 2,047 characters. This printer has a print speed of 100 characters/second (8 x 9 matrix printing).

Each component will be discussed separately.



#### 2.4.1.1 The IBM Personal System/2 Model 30

This computer consists of a system unit and a keyboard (ref.[19]). The system unit is the central part of the computer that supports a variety of options. The 3<sup>1/2</sup> inch diskette drive is provided to read/write data from/to a diskette. The keyboard, to send data to the system unit, is attached by a coiled cable. The various features of the system unit, with display and the keyboard, are shown in Fig.2.22, where both front and rear views are given.

##### Installation

Follow these steps:

Step 1: Be sure the system unit power switch is off.

Step 2: Connect the keyboard cable to connector 1 on the system unit and to the keyboard.

Step 3: Switch off the power switch on the display and place the display on top of the system unit.

Step 4: Connect the display signal cable to connector 5 on the system unit and tighten the thumb-screws.

Step 5: Connect the power cord for the display.

Step 6: Connect the power cord to the system unit, then plug it into a properly grounded electrical outlet.

Fig. 2.22: The Computer System of the Surveying System (not available).

In order to start the system, or if one runs into problems, refer to [19]. A self-test is provided in this reference.

#### 2.4.1.2 The IBM Personal System/2 Display

The IBM Personal System/2 Display is a direct-drive analog display (ref.[20]). Fig.2.23 shows locations of various controls, such as contrast, brightness, power switch, etc.

#### Connecting the Computer to the Display Monitor

To connect the monitor to the computer, follow these steps:

Step 1: Turn off the system.

Step 2: Attach the display signal cable to the 15 pin D-shaped display connector on the system unit.

Step 3: Tighten the screws.

Step 4: Plug the display power cord into the display first, then into a properly grounded electrical outlet.

Step 5: Adjust the brightness control until the background just disappears and turn the contrast to its maximum position (toward the front of the display).

For more details, refer to [21].

Fig. 2.23: The Display of the Surveying System (not available).

#### 2.4.1.3 The OKIDATA Microline 182 Printer

The printer used in the laboratory is basically a parallel printer (ref.[20], Fig. 2.24).

##### Connecting the Computer to the Printer

One should have a parallel interface cable to connect the computer to the printer. Make sure both the computer and the printer are *off* at this point.

Step 1: Insert the 36-pin plug into the appropriate receptacle towards the right side of the rear of the printer.

Step 2: Snap the two wire chips onto the plug.

Step 3: Insert the other end of the cable into the computer.

Step 4: Turn on the computer and the printer. The printer should, under normal working conditions, respond to any print command from the computer. Only rear-feed the paper to the printer. If there are problems, refer to [21].

There are four buttons (SEL, TOF, FORM Feed, LINE Feed) on the front panel. In addition, there are three indicator lights (POWER, SEL, ALARM) that show the current status of the printer.

#### 2.4.2 THE KIT-2 DIGITAL THEODOLITES

Two KIT-2 Digital Theodolites (ref. [22]) are used for the project in order to survey the tunnel floor (Fig. 2.25). Through an RS-232 Interface, communications is established between the theodolite and software package via the computer (socket # 4 on the rear side

Fig. 2.24: The Printer of the Surveying System (not available).

Fig. 2.25: The Digital Theodolite (not available).

of the computer) by means of a multiplexer (since two theodolites are used, Fig. 2.26). Each has a microprocessor programmed to combine optics and mechanics; and to measure angles like a conventional theodolite, except that the angles are interpolated automatically by K+E encoders and displayed directly, up to a resolution of 1 second, on the Liquid Crystal Display (LCD) of each theodolite. Each theodolite is equipped with LCD, two lines alphanumeric (20 characters per line), simultaneously displaying azimuth and elevation angles (in degrees or grads, which is user-defined) at all times. Each is also equipped with two electronic tilt sensors, one for vertical axis mislevel, and the other for horizontal axis mislevel in any direction (resolution is + 0.1 arc sec). These sensors are used to assure absolute level of the theodolites, and hence get more accurate results, during the setup leveling process.

#### 2.4.3 SYSTEM INITIALIZATION PROCEDURE

Follow these steps:

Step 1: Level the theodolites mechanically by adjusting the four leveling screws (which are under the alidade), two at a time until the theodolite bubble level is parallel to a line through the centers of a pair of opposite leveling screws.

Step 2: Turn on the main power switch; and the theodolites power switch. The operator must do in steps what the theodolite LCD messages say. When the message reads: *INDEX TELESCOPE* ; slowly rotate the telescope so that it passes through the  $90^{\circ}$  position to the horizontal in order to set the vertical index. The next message reads: *INDEX ALIDADE* . In that case, rotate the alidade through  $360^{\circ}$ . At this time, the display will read the vertical and horizontal angles on the first line; and the level 1 and 2 readings on the second line. Again adjust the leveling screws so that level 1 and 2 for each theodolites reads zero (or close to zero) on the display.

Fig. 2.26: The Multiplexer for the Surveying System (not available).

Step 3: Next, the theodolites are aimed at a horizontal reference target to automatically establish an *Azimuth Zero Reference* of the tilt sensors.

Step 4: The theodolites are pointed mutually at their coaxial alignment targets in order to record the relative angular orientation by means of the computer. These readings become the reference from which all horizontal angles are measured. The vertical angles are automatically referenced to gravity. This procedure sets up the default co-ordinate system, with positive x-axis as the line joining theodolite #1 to theodolite #2.

Step 5: Next, absolute orientation (and a scale factor) is recorded by pointing the theodolites successively at two fixed reference targets with known distance between them.

Step 6: The measurements are made by pointing the theodolites at the designated targets. The coordinates of these targets are computed and displayed with the distance from the preceding point. The results are displayed on the CRT, printed and stored.

#### 2.4.4 RUNNING THE AIMS II SOFTWARE

In this section, we shall carry the user through steps that are required to run the software as well as the theodolites, in a proper sequence, in order to survey the floor targets efficiently.

Step 1: When the computer is turned on, type in the following command:

*aimload*

Step 2: The following options will be displayed on the monitor:

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- (1) Start AIMS System*
  - (2) Calibrate KIT Theodolites*
  - (3) Change the Configuration*
  - (4) EXIT*
- Make your selection (1-3)?*

Choose option # 1 and hit <ENTER>.

Step 3: Next display on the monitor will be:

*Measurements in (1) DEGREES (2) GRADS*  
*Select (1-2)?*

Choose option # 1 and hit <ENTER>.

Step 4: The options displayed next will be:

*Measurements in (1) INCHES (2) MILLIMETERS*  
*Select (1-2)?*

Choose option # 2 and hit <ENTER>.

Step 5: The next option displayed on the screen will be:

*Do you want the session output to go to*  
*<1>. Printer*  
*<2>. A disk file named PRINTER.DAT*  
*Input a 1 or a 2?*

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Choose option # 1 and hit <ENTER>.

Step 6: Next display will allow the user to insert some comments, so that we know exactly where we are and what we have been doing for later analysis of data. The display will be:

*YOU MAY NOW TYPE AN UNLIMITED NUMBER OF COMMENT LINES. WHEN  
THROUGH WITH COMMENTS, JUST HIT (ENTER).*

Enter the comment: *Surveying the Lab Floor* and hit <ENTER>. Lot of data will appear on the screen, with the final message that reads:

*When READY hit (ENTER) key*

Hit <ENTER>.

Step 7: Next, the program will ask:

*THEODOLITES 1 AND 2 ARE ASSUMED TO BE ON-LINE (Y/N)?*

Enter *Y* for yes assuming the initial setting of the theodolites has been done.

Step 8: Next question to be asked will be:

*CALIBRATE TILT SENSORS OFFSETS FOR UNITS 1 2 (Y/N)?*

Enter *Y* .

Step 9: Another message displayed will be:

*FOR UNITS 1 AND 2 TAKE REVERSED READING OF ZERO AZIMUTH TARGET  
When READY hit (ENTER) key.*

Take the reversed reading of a zero azimuth target by pointing the two theodolites in reversed mode to the target, and then hit <ENTER>. In this mode, the position of the alidade is such that the bubble level faces the operator. The data will be electronically transferred to the computer and displayed on the screen.

Step 10: Next display will be:

*FOR UNITS 1 AND 2 TAKE DIRECT READING OF ZERO AZIMUTH TARGET  
When READY hit (ENTER) key.*

Take the direct reading of the zero azimuth target by pointing the two theodolites in direct mode to the target, and then hit <ENTER>. In this mode, the LCD of the alidade faces the operator. One can go from one mode to another by simply rotating the alidade and the telescope through 180°. The data will again be displayed on the screen.

Step 11: Type *Y* to the following message:

*Store new corrections (Y/N)?*

Do not hit <ENTER>. Wait for the following message to appear on the screen:

*NEW CORRECTIONS BEING STORED, please wait . .*

Do wait until the following message is displayed on the screen:



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*END OF CALIBRATION PROCEDURE.*

*to continue hit (ENTER) key*

Hit <ENTER>.

Step 12: Hit <ENTER> after the following message appears on the screen:

*AFTER LEVELLING, POINT BOTH THEODOLITES AT AZIMUTH REFERENCE TARGET,  
WHEN READY TO TAKE DIRECT READINGS hit (ENTER) key*

Step 13: Type *N* to the next message which reads:

*IF YOU WISH TO MAKE CORRECTIONS FOR ANY VERTICAL INDEX ERROR,  
YOU WILL HAVE TO ALSO TAKE A REVERSED READING OF  
AZIMUTH REFERENCE TARGET. (Y/N)?*

Do not hit <ENTER>.

Step 14: Type in *N* to the next message that reads:

*RESTARTING AN UNDISTURBED SETUP (Y/N)?*

Do not hit <ENTER>.

Step 15: The next message reads:

*To SCALE your Coordinate System you may enter  
DISTANCE between or XYZ coordinates of KNOWN two targets.*

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*IS DISTANCE BETWEEN FIXED TARGETS KNOWN (Y/N)?*

Type *Y* and wait for the following message to appear:

*ENTER KNOWN DISTANCE [inch]?*

Enter *39.3694* which is the length of the calibration rod, the two ends of which are supposed to be viewed through the theodolites.

Step 16: Before shooting the two ends (marked) of the calibration rod, we need to establish a default co-ordinate system when the following message appears:

*INITIALLY, MUTUALLY POINT THEODOLITES TO EACH OTHER  
WHEN READY TO TAKE DIRECT READINGS hit (ENTER) key*

Mutually point theodolites to each other in direct mode and hit <ENTER>. The next display should ask for reversed readings by displaying the following message:

*YOU MUST TAKE REVERSED READINGS  
WHEN READY TO TAKE REVERSED READINGS hit (ENTER) key*

Point theodolites to each other in reverse mode and hit <ENTER>.

Step 17: The user will now be instructed to shoot the 0" mark on the calibration rod by displaying the following messages:

*NEXT, POINT THEODOLITES AT TARGET For SCALING Point 1  
EVENT COUNTER WILL CONTINUE WITH 1*

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### *GENERAL PROMPT:*

*You may type a comment,  
measure a target (with ENTER),  
or use a menu function (with the <F5> key)*

=>

Type *Shooting point # 1 of the meter rod* at the prompt sign =>. From now onwards, the *GENERAL PROMPT* will be displayed every time a target is surveyed, so that one can write some comments about the point before shooting it. Hit <ENTER> when ready. The data will be transferred to the computer and displayed on the screen. From now onwards, the user is provided with an option to take reverse readings. During the initial setup of the system, it is advised to take readings in both modes. From this stage, all the surveyed points will be stored on the hard disk as stacks. The message provided reads:

*OPTIONAL REVERSED READINGS (Y/N)?*

Type *Y*. Another message will be displayed:

*WHEN READY TO TAKE REVERSED READINGS hit (ENTER) key*

When ready, hit <ENTER>. The user will be required to shoot another marked end of the calibration rod by going through the same sequence of messages as are mentioned for 0" mark on the rod, with the only difference that we are shooting point # 2 instead of point # 1. Take readings in both modes.

Step 18: Hit <ENTER> when the following message is displayed on the screen:

*THIS BRAND NEW COORDINATE SYSTEM WILL BE STORED AS 3  
IF YOU HIT (ENTER)  
OR MAY ASSIGN A NUMBER BETWEEN 3-20?*

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Type *N* to the following message:

*DO YOU WISH TO REDEFINE YOUR COORDINATE SYSTEM TO THE LAST TWO MEASURED TARGETS (Y/N)?*

Step 19: In order to choose a new co-ordinate system, we need to choose a command from the main menu listing. One can get to this listing by hitting <F3>. From this listing, choose *a4* and hit <F5>. The operator will be asked:

*<RE-ZERO COORDINATE SYSTEM> (Y/N)?*

Type *Y* and wait until the following message appears

*NEXT, POINT THEODOLITES AT TARGET  
EVENT COUNTER WILL CONTINUE WITH 7*

*GENERAL PROMPT:*

*You may type a comment,  
measure a target (with ENTER),  
or use a menu function (with the <F5> key)*

*=>*

It is nice to change our readings into *millimeters* and *degrees* by typing the sequence *a11* <F5> and *b11* <F5> respectively. The notation <F5> stands for hitting the function key # 5.

We are ready to make measurements, starting with the origin (0,0,0) and a target almost 2 meters west of the origin across the hall. We need at least two targets to establish this new co-ordinate system, called the *PRS*, with one target directly under

camera # 6 as the origin of the PRS and the other target defining the positive u-axis towards the west. The other axis (v) is defined to be the one which runs along the length of the tunnel, positive direction being towards the south. The z-axis is the one which is at right angles to the plane defined by (u,v) axes and runs through the origin.

Next, type *Origin (0,0,0)* at the *GENERAL PROMPT* and hit <ENTER> key when ready to take readings (preferably in both modes). Survey another point, using same procedure, along the u-axis and roughly 2 meters from the origin.

Step 20: Type *Y* to the next display:

*DO YOU WISH TO REDEFINE YOUR COORDINATE SYSTEM TO THE LAST TWO  
MEASURED TARGETS (Y/N)?*

Step 21: Type *0* to next two messages, which read:

*TO ROTATE COORDINATE FROM AZIMUTH LINE DEFINED BY LAST TWO TARGETS,  
TYPE ANY ANGLE INCREMENT YOU WISH (in degrees).*

*+X towards +Y is considered positive.*

*NEARLY ALWAYS, YOU WILL WANT ZERO.*

and

*LAST 2 TARGETS WERE x.xxxxx DEGREES FROM HORIZONTAL  
TO KEEP X-AXIS LEVEL, TYPE ZERO, OR TYPE LAST DECIMAL  
ANGLE, AND X-AXIS WILL BE MISLEVELED BY THAT AMOUNT.?*

*x* represents an integer. Type *0,0,0* to the following message:

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*YOU MAY NOW TRANSLATE THE ORIGIN BY ANY AMOUNT, PARALLEL TO YOUR  
NEWLY ROTATED COORDINATE SYSTEM.*

*X USUALLY RUNS SOMEWHAT HORIZONTAL, Z UPWARDS, Y AT RIGHT  
ANGLES TO THESE TWO BUT NOT ALWAYS. IT ALL DEPENDS ON ORIENTATION OF 1st  
TWO TARGETS. REGARDLESS, YOU MUST NOW TYPE THE NOMINAL X,Y,Z  
DIMENSIONS TO THE ASSIGNED TO THE NEXT-TO-THE-LAST TARGET ?*

Hit <ENTER> key couple of times. The next message displayed will be:

*YOU ARE INVITED TO TYPE SOME DESCRIPTION OF THIS COORDINATE SYSTEM  
FOR CONVENIENCE OF LATER REFERENCE*

Type *PRS* and hit <ENTER>.

Step 22: Shoot third target along the v-axis, roughly 4 or 5 meters from the origin. Type *N* to the following message:

*DO YOU WANT TO USE THIS TARGET TO CONTROL & PITCH THE Z-AXIS  
OUT OF GRAVITATIONAL PLUMB (Y/N)?*

Having established the *PRS* co-ordinate system, we are ready to survey other optical targets. Write proper comments at *GENERAL PROMPT* so as to keep track of the proceedings. Take readings only in direct mode in order to speed up the survey of floor targets. Type *a14* and hit <F5>, so that the program does not ask for an optional reversed reading when we are through with the direct reading of a target.

Step 23: It is a good practice to shoot some optical targets which are on the west and

east side walls of the tunnel and note down their co-ordinates with reference to the *PRS* origin. This is done so that the theodolites could be moved, at least couple of times, to different locations. It becomes extremely hard to shoot distant points as the viewing angles become narrower and we can end up in erroneous results. The so-called *TRI-POINT Routine* is used for this purpose, which can be invoked by typing *a13* and hitting <F5> at *GENERAL PROMPT* . At a different location, the theodolites and the AIMS II software program are initialized as before so that the default co-ordinate system is chosen at that location. The three reference targets on the side walls are measured in the same order as they were with reference to the *PRS* co-ordinate system earlier. Then the *TRI-POINT Routine* is invoked. The messages will ask for the previous co-ordinates of these point (with reference to *PRS* co-ordinate system). The program will readjust those values, and ask the operator whether those values are acceptable. If *Y* is typed, we are in *PRS* co-ordinate system, and all the points that we shoot from now onwards will be surveyed with respect to the *PRS* co-ordinate system.

After the task is accomplished, one can get a printout of all the surveyed targets by typing *a10* and hitting <F5>. To exit the program, type *c9* and hit <F5>.

**SECTION B**

**MATHEMATICAL MODELING  
OF THE  
POSITION REFERENCE SYSTEM**



## MATHEMATICAL MODELING OF THE PRS

### 3.1 OVERVIEW

In this section, the following three topics will be discussed (Fig. 3.1):

- # Operating Modes
- # Geometric Corrections
- # Determination of State Vector

Different operating modes of the PRS are described first. A technique is presented to calibrate cameras *off-line* before any real testing of the algorithms is done to determine the state vector of the PRS targets.

Fig. 3.2 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 *a priori* locations. 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 co-ordinates  $(x,y)$  of the targets are changed to floor co-ordinates  $(u,v)$  by mapping out the distortion effects and other errors. Off-line processing is done in order to calibrate each camera. For this purpose, the 3-D floor co-ordinates relative to a *reference* co-ordinate system and their corresponding 2-D image co-ordinates 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 co-efficients for each camera that account for the lens distortions and errors.

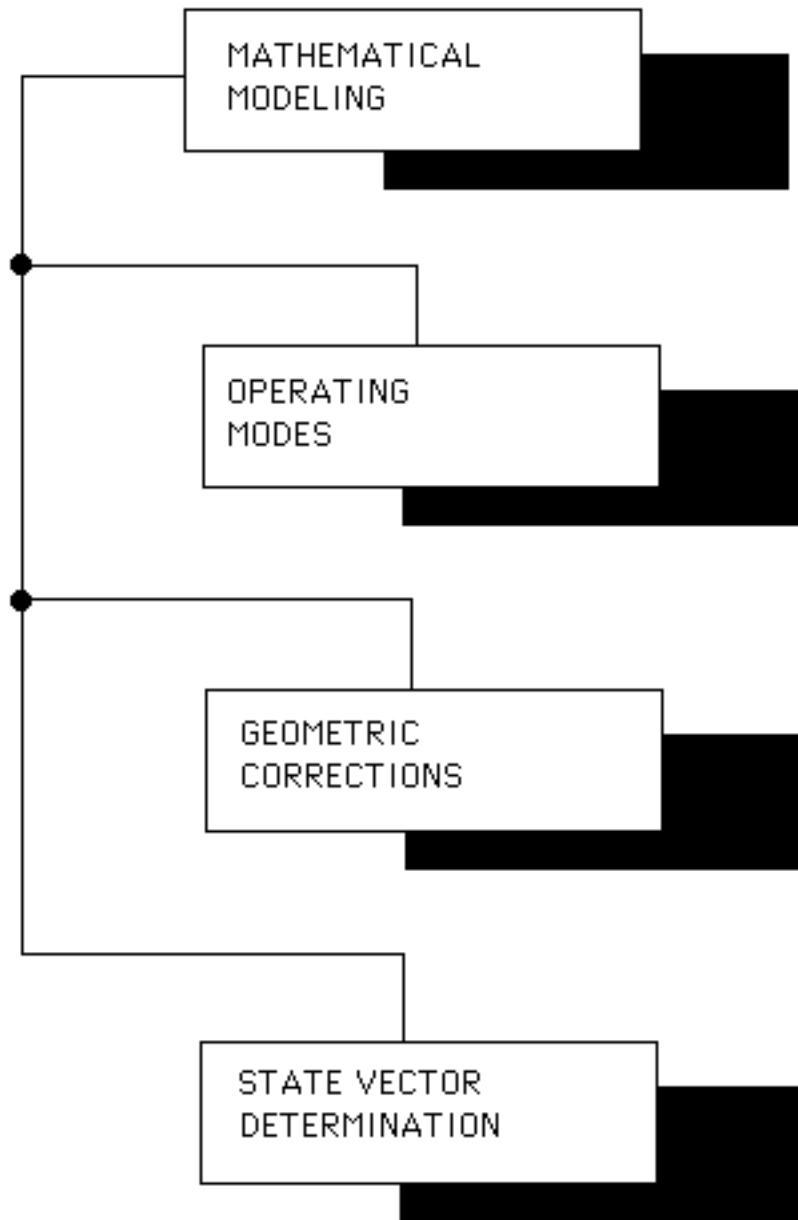


Fig. 3.1: Various components of the Mathematical Modeling of PRS.

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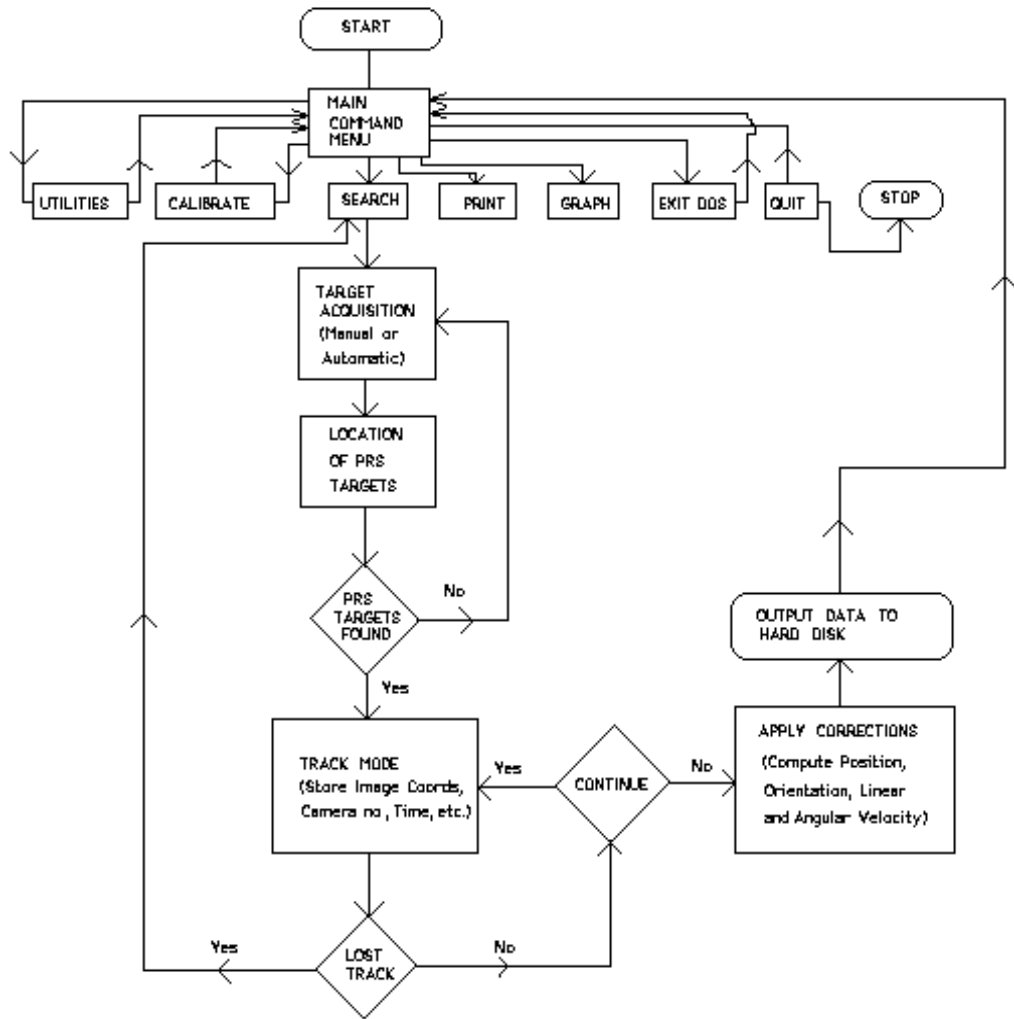


Fig. 3.2: Flow Chart for PRS Software Development.

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Once the PRS targets are found, the PRS program goes into the track mode. The program automatically tracks the robot by storing the (x,y) locations of the PRS target(s) on hard disk of the main computer, and by switching between the cameras if the robot moves from one FOV to the other. If the program loses track of the robot, it will automatically go back in search mode to look for the PRS targets. The operator can then do some off-line processing to map (x,y) co-ordinates to (u,v) co-ordinates; 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.

### 3.2 OPERATING MODES

The PRS program essentially works in five distinct operating modes (Fig.3.3). Table 3.1 gives a brief description of the different operating modes that have been used in the PRS program :

Table 3.1: Different Operating Modes

<u>Mode No.</u>	<u>Mode Name</u>	<u>Description</u>
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

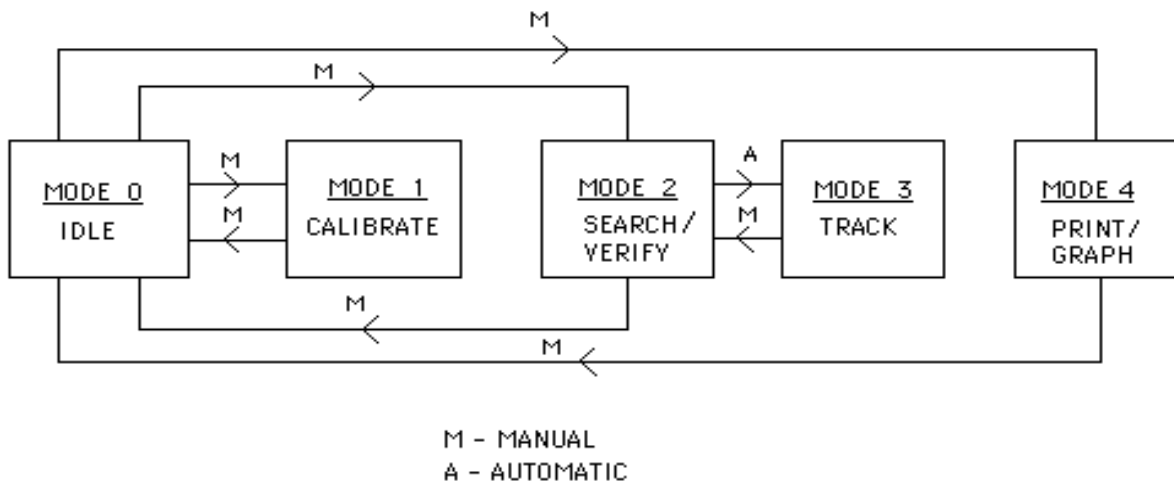


Fig. 3.3: Operating Modes and Transitions.

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When invoked, PRS program will display the *Main Command Menu* (MCM) screen/window indicating the system is in an idle state. This window will allow an operator to select an operating mode by hitting an assigned key. Mode options and various other commands will be displayed with *labels* along the bottom of the screen.

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

### 3.2.1 IDLE MODE

In this mode, the display (MCM window) indicates an *idle state*. The software accepts keystrokes to perform rest of the modes. No operations are performed in this mode.

### 3.2.2 CALIBRATE MODE

In this mode, the software determines the image co-ordinates  $(x,y)$ , in a particular camera's FOV, of special optical targets (calibration points) whose precise  $(u,v)$  locations are known. The  $(u,v)$  co-ordinate information is entered once by the operator and is used along with the  $(x,y)$  co-ordinate information to determine the *geometric calibration co-efficients* of the cameras.

The calibration co-efficients are stored in a historical file, called *CALIBRAT.DAT* and supplied to TRACK mode after the  $(x,y)$  co-ordinates the target(s) are stored on the hard disk.

### 3.2.3 SEARCH MODE

The steps of operation in this mode, after this mode has been selected from the IDLE mode, are as follow:

Step 1: Grab a frame from the primary camera. Default to camera number 6 (which can be changed in the *Utilities* option of the IDLE mode), or choose a camera manually by means of a mouse. The image is transferred from the *MVP-AT/NP* frame grabber to the computer memory. (A HUGE memory buffer of 256K has been reserved for this purpose during the initialization of the program.)

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 border 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.

d. Increment the column pointer by 2 (`X_SEARCH_INCREMENT` in `prs\include\prs.h`) so as to search only every other column for targets.

e. Increment the row pointer likewise (`Y_SEARCH_INCREMENT`) to search only 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 threshold limit for the camera is reached.

Step 5: If any other candidate targets have been located, check distances between each in (x,y) co-ordinates for matching, within tight tolerances, the three inter-target distances (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 around each target so that the operator has an idea/confirmation of the valid targets.



### 3.2.4 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 for. The size of the rectangle may be adjusted by changing the parameters in the file *prs\include\prs.def*. If the target is found, the target position is updated and the tracking is continued.

Step 2: If the target is not found, the previous step will 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 by hitting <ESC> key or <F10> key.

### 3.2.5 PRINT/GRAPH MODE

In this mode, the state vector (position, orientation, linear and angular velocities and accelerations) of a target as a function of time, can be printed out or plotted.

### 3.3 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. In this section, we shall present the following:

- # Calibration of CCD cameras
- # Forward transformations (conversion of image co-ordinates to floor co-ordinates)
- # Target-height correction

A detailed analysis follows.

#### 3.3.1 CALIBRATION OF CCD CAMERAS

Each camera is characterized by some set of single-precision, floating-point coefficients. 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, keystoneing, 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 (video) co-ordinates 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. 3.4). Let  $(u,v)$  be the floor co-ordinates with the origin directly under 6<sup>th</sup> 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 floor co-ordinates  $(u_j,v_j)$  of the optical targets in  $j^{\text{th}}$  camera's FOV are related to their corresponding image co-ordinates  $(x_j,y_j)$  as

$$u_j = P_{y,j}^T A_{\Gamma_j} P_{x,j} \quad \text{and} \quad v_j = P_{y,j}^T B_{\Gamma_j} P_{x,j} \quad (3.1a)$$

where

$$P_{x,j} = [ 1, x_j, x_j^2, x_j^3 ]^T \text{ and } P_{y,j} = [ 1, y_j, y_j^2, y_j^3 ]^T \quad (3.1b)$$

for third-order terms. Only terms up to third-order are accepted in this calibration scheme.  $A_{\Gamma_j}$  and  $B_{\Gamma_j}$  are the *camera coefficient matrices* for the  $j^{\text{th}}$  camera, and are given as

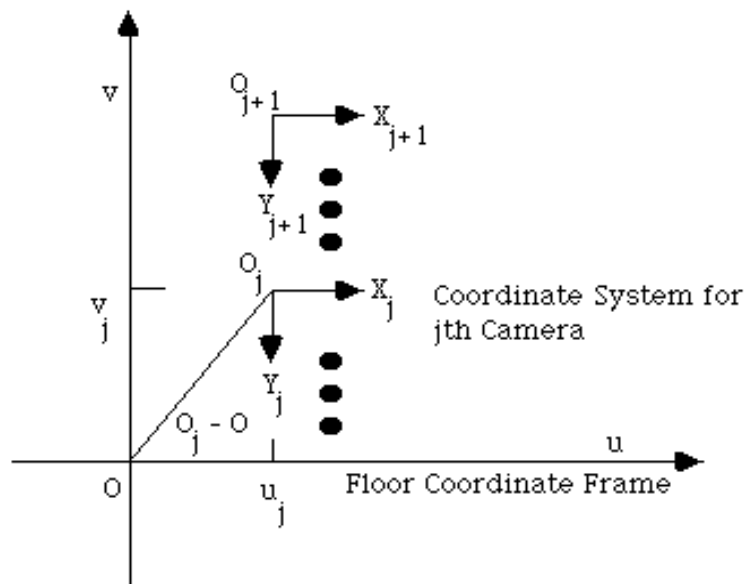


Fig. 3.4: Relationship between Floor Co-ordinate Frame (or the Reference System) and different Camera Co-ordinate Frames.

$$A_{r_1} = \begin{bmatrix} A_{0,j} & A_{1,j} & A_{4,j} & A_{9,j} \\ A_{2,j} & A_{3,j} & A_{6,j} & A_{11,j} \\ A_{5,j} & A_{7,j} & A_{8,j} & A_{13,j} \\ A_{10,j} & A_{12,j} & A_{14,j} & A_{15,j} \end{bmatrix} \quad \text{and} \quad B_{r_1} = \begin{bmatrix} B_{0,j} & B_{1,j} & B_{4,j} & B_{9,j} \\ B_{2,j} & B_{3,j} & B_{6,j} & B_{11,j} \\ B_{5,j} & B_{7,j} & B_{8,j} & B_{13,j} \\ B_{10,j} & B_{12,j} & B_{14,j} & B_{15,j} \end{bmatrix}$$

(3.2a,b)

The above equations can be re-written, for  $n$  calibration points ( $n > 16$ ) with known  $(u,v)$  and corresponding  $(x,y)$  co-ordinates, in the following manner:

$$F_j = AB_{\Gamma_j} l_j \quad (3.3a)$$

where the *floor matrix*  $F_j$  contains the floor co-ordinates of the floor targets (in  $j^{\text{th}}$  camera's FOV) as its elements, the *image matrix*  $l_j$  has the corresponding image co-ordinates as its elements, and the *coefficient matrix*  $AB_{\Gamma_j}$  has the unknown calibration coefficients for the  $j^{\text{th}}$  camera. These matrices are

$$F_j = \begin{bmatrix} u_{1,j} & u_{2,j} & \dots & u_{n,j} \\ v_{1,j} & v_{2,j} & \dots & v_{n,j} \end{bmatrix} \quad (3.3b)$$

$$AB_{\Gamma_j} = \begin{bmatrix} A_{0,j} & A_{1,j} & \dots & A_{n,j} \\ B_{0,j} & B_{1,j} & \dots & B_{n,j} \end{bmatrix} \quad (3.3c)$$



targets are viewed. This type of mapping of (x,y) into (u,v) is called the *forward transformation*.

### 3.3.2 FORWARD TRANSFORMATIONS

The following equations convert camera (x,y) co-ordinates into floor (u,v) co-ordinates:

$$u_j = [(A_{15,j} * xy + A_{14,j} * y + A_{13,j} * x + A_{8,j}) * xy + (A_{12,j} * y + A_{7,j}) * y + (A_{11,j} * x + A_{6,j}) * x + A_{3,j}] * xy + [(A_{10,j} * y + A_{5,j}) * y + A_{2,j}] * y + [(A_{9,j} * x + A_{4,j}) * x + A_{1,j}] * x + u_{int,j} \quad (3.5a)$$

and

$$v_j = [(B_{15,j} * xy + B_{14,j} * y + B_{13,j} * x + B_{8,j}) * xy + (B_{12,j} * y + B_{7,j}) * y + (B_{11,j} * x + B_{6,j}) * x + B_{3,j}] * xy + [(B_{10,j} * y + B_{5,j}) * y + B_{2,j}] * y + [(B_{9,j} * x + B_{4,j}) * x + B_{1,j}] * x + v_{int,j} \quad (3.5b)$$

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

### 3.3.3 TARGET-HEIGHT CORRECTION

Using the above-mentioned techniques, the floor-projected target co-ordinates are known to us, not the floor co-ordinates of the targets. It is so because the target plane is at some known height above the floor and the camera above it views these targets radially (Fig.3.5).

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

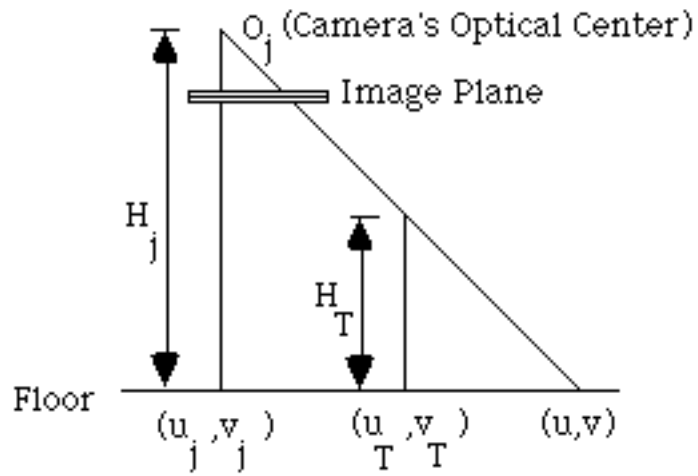


Fig. 3.5: Target-Height Correction Geometry.



$H_j$ , the height of a given camera

$H_T$ , the height of the target ( $H_T \ll H_j$ )

$(u_j, v_j)$ , camera sub-point co-ordinates

$(u, v)$ , floor-projected target co-ordinates

the *height-corrected* co-ordinates  $(u_T, v_T)$  of the target can be found as, using similarity of triangles approach,

$$u_T = \lambda_1 u + \lambda_2 u_j \quad \text{and} \quad v_T = \lambda_1 v + \lambda_2 v_j \quad (3.6a,b)$$

where

$$\lambda_1 = (H_j - H_T)/H_j \quad \text{and} \quad \lambda_2 = H_T/H_j \quad (3.6c,d)$$

### 3.4 DETERMINATION OF STATE VECTOR

The *State Vector* of a PRS target 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.

### 3.4.1 POSITION

The 2-D image co-ordinates of PRS targets are stored real-time. These co-ordinates are later converted into target-height corrected floor co-ordinates (sec. 3.3.3; equation (3.6a,b,c,d)). These target-height corrected co-ordinates give the *position* of target(s) at any instant of time.

### 3.4.2 LINEAR VELOCITY AND ACCELERATION

The two components of *linear velocity* ( $\eta_{u,i+1}$ ,  $\eta_{v,i+1}$ ) of the targets along u- and v-axes, at instant  $t_{i+1}$  ( $i > 0$ ), are given as:

$$\eta_{u,i+1} = (u_{i+1} - u_i)/\Delta t \text{ and } \eta_{v,i+1} = (v_{i+1} - v_i)/\Delta t \quad (3.7a,b)$$

where

( $u_{i+1}$ ,  $v_{i+1}$ ) represent the position of a target at instant  $t_{i+1}$ ;  
 ( $u_i$ ,  $v_i$ ) the position of the target at instant  $t_i$ ; and  
 $\Delta t = t_{i+1} - t_i$ .

Similarly, the two components of *linear acceleration* ( $\Omega_{u,i+1}$ ,  $\Omega_{v,i+1}$ ) of the targets at instant  $t_{i+1}$  are given as:

$$\Omega_{u,i+1} = (\eta_{u,i+1} - \eta_{u,i})/\Delta t \text{ and } \Omega_{v,i+1} = (\eta_{v,i+1} - \eta_{v,i})/\Delta t \quad (3.7c,d)$$

### 3.4.3 ORIENTATION

A minimum of two PRS targets are tracked over a period of time in order to compute the *orientation*. The angle, which gives orientation of the robot relative to the positive u-axis, is measured in counter-clockwise sense. Let, at any instant  $t_i$  ( $i > 0$ ),  $(u_{1,i}, v_{1,i})$  and  $(u_{2,i}, v_{2,i})$  be the positions of any two targets. Define:

$$\text{Sine}_i = (v_{1,i} - v_{2,i})/\text{DISTANCE} \quad \text{and} \quad \text{Cosine}_i = (u_{1,i} - u_{2,i})/\text{DISTANCE} \quad (3.8a,b)$$

where DISTANCE represents the *actual* distance between the two targets. The *angle of rotation* is then defined to be

$$\theta_i = \text{arctangent}(\text{Sine}_i/\text{Cosine}_i) \quad (3.8c)$$

Since an *arctangent* function has two arguments, proper value of  $\theta_i$  can be found out (i.e., angle in proper quadrant) by observing the signs of  $\text{Sine}_i$  and  $\text{Cosine}_i$  functions in equation (3.8a,b) at each instant  $t_i$ .

### 3.4.4 ANGULAR VELOCITY AND ACCELERATION

The *angular velocity* ( $\omega_{i+1}$ ) of the targets, at instant  $t_{i+1}$  ( $i > 0$ ), is given as:

$$\omega_{i+1} = (\theta_{i+1} - \theta_i)/\Delta t \quad (3.9a)$$

where

$(\theta_{i+1})$  represents the orientation of the targets at instant  $t_{i+1}$ ;

$(\theta_i)$  the orientation of the targets at instant  $t_i$ ; and

$\Delta t = t_{i+1} - t_i$ .

Similarly, the *angular acceleration* ( $\alpha_{i+1}$ ) of the targets at instant  $t_{i+1}$  is given as:

$$\alpha_{i+1} = (\omega_{i+1} - \omega_i)/\Delta t \quad (3.9b)$$

**SECTION C**

**EXPERIMENTAL RESULTS**

## EXPERIMENTAL RESULTS

### 4.1 OVERVIEW

In this chapter, we shall present various test results, in form of print-outs and plots, of the PRS. Accuracy analysis, based on a random experiment, will be performed. The technical specifications of the system are also presented. First, we shall describe the procedure of the calibration of the CCD cameras.

### 4.2 PROCEDURE FOR CALIBRATION OF CCD CAMERAS

In the PRS laboratory, the robot is tracked by CCD cameras, numbered 1 through 11, which are mounted on the ceiling and look vertically downwards. The robot, which moves on the tunnel floor, is monitored by means of the control unit stationed at the mezzanine. The robot carries three miniature bright lights, or PRS targets, with a dark background, that enable the tracking system to easily identify the PRS targets.

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, presented in ref. [23], where sub-pixel accuracy could be achieved. Time was the only limiting factor. The 3-D locations of the optical targets (u, v, z) with their 2-D image locations (X, Y) under proper camera number (Camera#) and designated PRS co-ordinates (prs\_u, prs\_v) are shown in print-out P1. All measurements were done in millimeters. The set of calibration coefficients for cameras 5, 6 and 7 are listed in print-out P2. All the print-outs and plots for test results are kept at the end of this section.

#### 4.3 DETERMINATION OF CAMERA HEIGHTS

The height of each camera, to be used later in height-correction of position co-ordinates, was recorded by means of the theodolites in the following steps:

Step 1: A lens cap, with the optical target on it, was kept on each camera. The center of this optical target was viewed through the theodolites. The surveyed co-ordinates (u, v, z) are listed in table 4.1.

Table 4.1: The surveyed heights of cameras

<u>Camera #</u>	<u>u(in mm)</u>	<u>v(in mm)</u>	<u>z(in mm)</u>
5	17.171	-3662.15	4819.663
6	2.748	-5.079	4816.692
7	5.277	3647.717	4822.507

Step 2: Next, the average distance between the lens cap and the optical center of each camera (the center of the CCD element) was found to be  $1\frac{3}{16}$  in. (or 30.1625mm). This was added to the height of each camera found in step 1.

Step 3: Since the floor is not perfectly horizontal, the heights of optical targets, or their z- co-ordinates, located at four corners of each camera's FOV were averaged to give the average height of the plane (viewed by camera) above the origin of the reference system. This height distance is to be subtracted from the height found in step 2. For these cameras, the average heights are listed in table 4.2.

Table 4.2: Average heights of the planes

<u>Camera #</u>	<u>Average Height of the Plane (in mm)</u>
5	4.24225
6	9.74625
7	8.69025

Step 4: Therefore, the corrected heights of these three cameras are listed in table 4.3. This information is stored in *prs\include\prs.h*.

Table 4.3: Corrected heights of cameras

<u>Camera #</u>	<u>Corrected Height (in mm)</u>
5	4845.58325
6	4837.10825
7	4843.98175



#### 4.4 CAMERA SETTINGS

Various *camera-settings* are listed in table 4.4.

Table 4.4: Camera Settings

<u>Camera #</u>	<u>Focus Setting</u>	<u>Focal Length/Aperture Ratio</u>	<u>NASA Tag#(ID)</u>
1	infinite	16	303672
2	0.2m	16	303679
3	0.2m	16	303675
4	0.2m	16	303678
5	0.2m	16	303684
6	3m - infinite	16	303685
7	0.2m	16	303686
8	infinite	16	303687
9	1.5m	11	303674
10	3.0m	11	303677
11	0.3m - 0.4m	11	303676

#### 4.5 VERIFICATION OF PRS TARGETS

The surface of the robot, like some screw-heads on the robot's surface, does sometimes reflect enough light to confuse the tracking system into accepting a false target. In order to circumvent this problem, the three lights are kept in a *right-angled* triangular fashion, and are provided with reflectors. Their *inter-target* distances are measured in each camera's FOV. If  $d1$  represents the smallest distance of the triangle these lights form, and  $d3$  the target, it was found that

$$16 < d1 < 22 \quad \text{and} \quad 32 < d2 < 42.$$

Measurements were done in *image units* , and at various regions of a particular camera's FOV. For our analysis, we chose

$$12 < d1 < 25 \quad \text{and} \quad 30 < d2 < 45.$$

Then, in order to verify the targets,  $d3$  has to be somewhat equal to the square root of the sum of the squares of  $d1$  and  $d2$  . The targets should also be designated as target #1, target #2, and target #3, so that the operator knows which target he/she is tracking. This can be done by choosing target directly opposite the largest side ( $d3$ ) to be target #1, and so on. This procedure will be needed later to find the orientation of the robot. Also, the actual inter-target distances were found to be

$$d1 = 192.0\text{mm}; d2 = 387.0\text{mm}; \text{ and } d3 = 433.0\text{mm}.$$

The height of the plane carrying these targets was found to be 1096.0mm. This information is later needed for height-correction of position co-ordinates, and stored in *prs\include\prs.h* . In order to speed-up the search of the targets, every other row and column of each snap are processed. In case, the tracking system fails to identify the targets, the user should go into *Utilities* menu of the software, move the robot a little, take a snap-shot from the required camera, and press function key <F1> to search for the targets. Three circles of different radii, smallest one corresponding to target #1 and so on, will be drawn around each target and displayed on the camera display monitor. If not, the user is advised to repeat these steps before he/she goes into the *Search* menu of the software.

#### 4.6 TEST RESULTS

Various experiments with the software written for PRS 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.

The various tests conducted are described in table 4.5.

Table 4.5: Various PRS experiments

<u>Test #</u>	<u>Description</u>
1	Only one target was tracked under a single camera. The robot was made to rotate.
2	Two targets were tracked under same camera's FOV. The robot was made to rotate.
3	Only one target was tracked. The robot made to rotate. Camera switching demonstrated.
4	Two targets were tracked. Camera switching demonstrated.

The description of various print-outs (labeled P3 through P6), corresponding to these four tests, are listed in table 4.6a.

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Table 4.6a: Various tests and corresponding print-outs

<u>Test#</u>	<u>Print-out#</u>	<u>Type of data</u>	<u># targets tracked</u>
1	P3	Image and position co-ordinates of target #1	1
2	P4(a)	Image and position co-ordinates of target #1	2
	P4(b)	Image and position co-ordinates of target #2	
	P4(c)	Linear Velocity and acceleration of target #1	
	P4(d)	Orientation, angular velocity and acceleration of targets	
3	P5	Image and position co-ordinates of target #1	1
4	P6(a)	Image and position co-ordinates of target #1	2
	P6(b)	Orientation, angular velocity and acceleration of targets	

The data of state vector is plotted against elapsed time (in seconds). Various plots (labeled G1 through G4), which correspond to the print-outs P3 through P6, are discussed in table 4.6b.

Table 4.6b: Various tests and corresponding plots

<u>Test#</u>	<u>Plots</u>	<u>Type of Plot</u>	<u># targets tracked</u>
1	G1(a)	Image co-ordinates of target #1	1
	G1(b)	Position co-ordinates of target #1	
2	G2(a)	Image co-ordinates of target #1	2
	G2(b)	Position co-ordinates of target #1	
	G2(c)	Position co-ordinates of target #2	
	G2(d)	Linear velocity of target #1	
	G2(e)	Linear acceleration of target #1	
	G2(f)	Orientation of the targets	

Table 4.6b (Contd.)

	G2(g)	Angular velocity of the targets	
	G2(h)	Angular acceleration of the targets	
3	G3(a)	Image co-ordinates of target #1	1
	G3(b)	Position co-ordinates of target #1	
4	G4(a)	Position co-ordinates of target #1	2
	G4(b)	Orientation of the targets	

The angle for determining orientation is zero when the smallest side of the triangle formed by lights, or the line joining the two targets being tracked, is parallel to the v-axis (down the tunnel) and is measured in *counter-clockwise* sense.

A rotation of the robot in test #1 will give a sinusoidal plot when this data is plotted against time. This fact is demonstrated in G1(a,b) and G2(a,b,c). The orientation will be represented by a saw-tooth plot (illustrated by G2(f)) if the angle keeps on increasing (i.e. robot keeps on rotating counter-clockwise).

#### 4.7 TECHNICAL SPECIFICATIONS

Table 4.7 gives technical specifications (at target height) of the PRS system.

Table 4.7: Technical specifications of PRS

Maximum <i>linear velocity</i> of the robot possible without losing track of the target(s)	18 in./sec (if one target tracked) 14 in./sec (if two targets tracked)
Maximum <i>angular velocity</i> possible without losing track of the target(s)	90°/sec (if one target tracked) 55°/sec (if two targets tracked)

Table 4.7 (Contd.)

Pixel size (camera # 6's video)	11.24mm x 9.56mm or 0.44in x 0.38in at the edges 10.93mm x 9.05mm or 0.43in x 0.36in at the center
Distance measured between two targets (random experiment)	0.382in or 9.713mm off at the center 0.308in or 7.834mm off at the edge (about 5% error)

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 perfectly horizontal. The floor height can, as a matter of fact, vary by about one centimeter or more under the same camera.

(ii) The camera is also assumed to be pointing vertically downwards.

(iii) 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.

(iv) 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 (and hence the fast tracking of the targets).

*All printouts and graphs not available in this document.*

## **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.

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