DESIGN AND IMPLEMENTATION OF AN AUTOMATED FLEXIBLE ASSEMBLY CELL FOR RESEARCH PURPOSES

by

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(ABSTRACT)

A better understanding of the assembly process and the technologies associated with automated assembly is needed for the successful development of a true flexible and intelligent assembly system. The development of more flexible peripherals and a better understanding of coordination and communication problems among the elements of the cell are some of the topics that require further investigation.

The objective of this project was to create an automated flexible assembly cell to be the test bed for basic and applied research in the areas of : (1) system configuration, (2) sensing, (3) end effector and manipulators, (4) part storage, feeding and presentation, and (5) part mating.

The implemented assembly cell contains three SCARA robots, a conveyor, a cell control computer, and communication and testing software. The cell is a mixed configuration: assembly line - single station, with two workstations. One workstation contains one robot and the other station holds two robots with overlapping work envelopes. The conveyor is a two-level closed loop configuration, controlled by a

programmable logic controller. The cell controller computer contains dedicated software for information integration and control operations within the cell. In order to achieve the final configuration of the assembly cell, requirements for the research areas were defined; and mechanical integration, electrical interconnecting, and communication software were designed and implemented.

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1 - INTRODUCTION

Increasing international competition and the rapid advance of technology have accelerated the industrial trends to reduce a product's life cycle, improve product quality, decrease production cost, reduce batch size, increase the variety of new products, and reduce the response time to market demand [1].

These industrial trends, associated with the proliferation of faster and cheaper computers, have triggered the development of more automated, flexible, and 'intelligent' manufacturing technologies. Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), Computer Integrated Manufacturing (CIM), Flexible Manufacturing System (FMS), and other computer-based technologies, are becoming common tools in the production environment [2]. The Manufacturing Systems area of the Industrial and Systems Engineering Department at Virginia Polytechnic Institute and State University has invested considerable concentration and effort into the research and understanding of these new technologies.

Presently, one of these efforts is the creation of the Manufacturing, Automation and Robotic Laboratory (MARL) to house integrated and automated manufacturing systems. The laboratory will include an automatic storage and retrieval system, a flexible manufacturing system, an automated flexible assembly cell, and other systems dedicated to specific topics of research.

An automated guided vehicle (AGV) system will be available for material integration among the various systems, and serial communication, via RS-232-C interfaces and/or local area networks (LANs), will accomplish the data integration inside the MARL.

The objective of this project was the design and implementation of the basic system of the automated flexible assembly cell. The result of the implementation of the project is a working assembly system, with basic software for cell control, monitoring, testing, and integration demonstration.

2 - PROBLEM STATEMENT AND OBJECTIVES

Successful industrial applications of flexible automated systems are frequently reported in the literature. A better understanding of the assembly process and the technologies associated with automated assembly, however, is needed for successful development of a true flexible and intelligent assembly system [3]. The design of products to ease the assembly operation; the development of more flexible peripherals, such as feeders, fixtures, sensors, and end effectors in the assembly work station; and a better understanding of coordination and communication problems among the elements of the cell are some of the topics that require further investigation [4].

The cell designed and implemented in this project aims to be a test bed for the research, implementation, and evaluation of models and techniques in the area of automated assembly.

A typical flexible assembly cell consists of one or more robots, a transfer mechanism, sensors, feeders, a computer control, and other dedicated equipment. These devices need to be arranged as required by the operations assigned to the station. Also, well-defined interfaces for material and/or data exchange among the robots, conveyor, and cell controller are fundamental for an integrated and synchronized operation of the cell.

In order to achieve the final design, a background review of the assembly process was done, potential areas for research in automated flexible assembly and their requirements were identified, and requirements of the Manufacturing, Automation and Robotic Laboratory were developed (as discussed in section 4.2).

3 - LITERATURE REVIEW

3.1 - INTRODUCTION

This literature review is divided into four sections. In the first section, the assembly activity and the three basic forms of assembly are identified. The next section contains a description of automated flexible assembly configuration and its main components. In the third section, some examples of the industrial application of flexible assembly systems and the respective advantages of using this technology are described. The last section identifies and exemplifies potential areas and topics for research using the proposed flexible assembly cell.

3.2 - BACKGROUND

Assembly involves the joining of two or more separated parts to form a new entity [1]. Assembly becomes necessary when the design effort cannot simplify the product into a one piece element. The most common processes to accomplish the assembly are mechanical fastening, joining methods, and adhesive bonding [5]. There are three basic means to accomplishing an assembly operation: manual, semi-automated, or automated [6].

In manual assembly the flexibility, intelligence, and dexterity of human assemblers make them extremely adept at assembly [7]. However, the operator's difficulty in maintaining the desired standards of quality, in executing complex operations (such as surface mount devices assembly in the electronic industry), and in performing high-speed assemblies are some deficiencies of this method of assembly [8].

Semi-automated assembly is an alternative that solves some of the limitations of human operators. The assembly operations are executed manually but are assisted by automated devices that control the presentation and sequence of components for the assembly operator. This approach can make the assembly process very efficient through the minimization of human error during assembly and the reduction of assembly time. Additionally, semi-automated assembly retains the human operator's high degree of flexibility in dealing with a variety of component shapes. The limitations of manual assembly for applications in high-speed assembly and complex operations, however, are only partially solved by the semi-automated assembly approach [6].

In automated assembly, all the joining operations are executed by machines, without any interaction with a human operator. Automated assembly can be implemented with specialized machines or flexible systems [5]. Specialized assembly systems consist of dedicated devices to assemble large quantities of products at high speed while maintaining uniform performance. To achieve this high volume of production, dedicated and expensive devices are required, making the cost of this alternative prohibitive for small batch assembly applications. It is also not suited for the diversity of items associated with many assembly situations [9]. In automated flexible assembly, robots, supported by other versatile devices, are used to offer some of the flexibility of manual assembly, with the uniform results of specialized assembly. These characteristics create a practicable alternative for diversified and small batch production [3].

3.3 - AUTOMATED FLEXIBLE ASSEMBLY CELL

There are two basic configurations for the flexible assembly systems, a single work station, and a series of work stations [10]. In a single-station robotic assembly system all sequence of assembly operations is executed at a specific station. It would typically be used for low to medium production volumes and where a limited number of assembly tasks and parts are to be handled.

In an assembly line configuration, a limited number of tasks are performed on the products at each work station, and the products are gradually built up as they move down the line. This type of configuration is mainly applied to medium to high production volumes. The typical components of a work station are robots, end effectors, feeders, transfer mechanisms, assembly fixtures, and sensors [11]. Ideally, all these components would have a certain degree of flexibility; however, at the present, for most applications the only really flexible elements are the robots, which are surrounded by dedicated fixtures and component feeders [12].

3.4 - INDUSTRIAL APPLICATIONS OF FLEXIBLE ASSEMBLY AUTOMATION

Industry has recognized the economic and strategic importance of automated flexible assembly systems [2,13]. The literature is rich in examples of successful applications of flexible assembly in the manufacturing industry. This section describes some of these examples to illustrate applications, cell configurations, and advantages of automated flexible assembly systems in the production environment.

Yamafuji and Makino [14] describe several applications of flexible assembly automation in the Japanese industry, including assembly of copy machines, small relays for automobiles, wrist watches, VCR mechanisms, and facsimile machines. The cell configuration in the assembly of facsimile machines includes two robots, a conveyor system, flexible parts feeding equipment with optical sensors for part selection, and quick-change end effectors. The main advantages of robotic assembly in these applications are (1) the flexibility of the systems, (2) the quick set-up of the production, (3) the re-utilization of the system for another application when production of a product is ended, and (4) the high and persistent quality of the products.

Scarborough [15] illustrates the application of flexible robotic systems in electronic printed circuit board assembly. The system consists of a robot, a conveyor system, a set of feeder devices, adjustable printed-circuit board locator and transfer devices, dedicated end effectors, a vision system, and a cell controller computer. The rapid component-change technology, component physical dimensions (standard and odd-shaped), concentration of components on the board, and reduction of product life cycle have influenced the push for flexibility and automation in the assembly of printed circuit boards.

Olsen [16] describes a flexible robotic workcell for the assembly of airframes components. The key workcell devices in the application are two robots, a flexible fixture, a metrology system, an automatic fastening machine, and several end effectors. Flexibility and work quality were the main criteria considered when developing the automated work cell.

An automated flexible assembly cell for application in the aerospace industry is described by Goodman [17]. The cell performs assembly, riveting, and inspection operations. The work station contains a vision system to inspect the tolerance of incoming parts, a flexible jig, automatic riveting equipment, and a robot. The goals of the system were to gain flexibility and to reduce tooling costs.

Branko [18] describes an automated flexible assembly system developed by U.S. Air Force applied to aircraft assembly manufacturing. The system includes two robots, diverse end effectors, a laser-driven metrology system, a programmable flexible fixture, an automated fastening machine, and a hierarchical computer control system. The objective of this application was to improve the flexibility and adaptability of automated assembly.

Two applications of automated flexible assembly of printed circuit board assembly are described by Liebes et al. [19] and Gast [20]. The systems allow both through-hole and surface-mount odd-shaped components onto printed circuit boards in arbitrary batch sizes, and use computer vision to examine components and boards. They incorporate sensor-based error detection and recovery, generic part feeders, general-purpose lead straightening, and lead clinching. The systems were designed to fit into the Just-In-Time manufacturing environment.

A wire harness assembly pilot workstation is described by Schraft, Schlaich, and Gohner [21]. The system consists of a SCARA robot, a set of grippers stored in a tool magazine, a fixed routing board, harness fixtures, and a vibratory bowl. The improvement of product quality and the reduction of assembly time by half are the primary gains of this system in comparison to previous manual assembly.

Martins [22] illustrates the implementation of an automated flexible system for assembly of a family of electro-mechanical contactors with more than fifty variants. The system consists of robots with multiple grippers, fixtures, vibratory bowl feeders, a conveyor system, and an automated testing machine. The main advantages of the automated assembly system in this application are low per-part cost, high availability, quick set-up, and short cycle time are .

A flexible system for the assembly of oscillating gear motors is described by Aregger and von Burg [23]. The system contains a variety of components, including automatic part feeders, a conveyor system, two robots, a set of grippers and special table stations for operations not executed by robots, such as pressing and bending. Automation flexibility and cost reduction were the main achievements in the application.

Arnstron, Holmstedt, and Erlandsson [24] describe a flexible system for air-motors assembly. Forty-three different types and models of air-motors can be assembled with the system. A robot, a vision system, automatic feeders, changeable grippers, and an indexing table are some of devices used in this application. The high efficiency rate (over 95%) and the full integration into a flexible manufacturing environment are the most important results of this application.

In summary, flexible assembly systems have been used in diverse areas in the manufacturing environment, with similar basic configurations: robots, dedicated part feeders, dedicated end effectors, dedicated grippers, and conveyor systems. The main advantages of these systems are their high efficiency, quick set-up, flexibility, and adaptability.

3.5 - RESEARCH OPPORTUNITIES IN FLEXIBLE ASSEMBLY AUTOMATION

Although the importance of automated assembly is well known, the progress of research in this area is minimal when compared to component manufacturing technologies

[4]. To advance the science and technology of the flexible assembly process, multiple challenging problems still need to be addressed. Soni [4] and Beery [25] identified several potential research opportunities and needs in flexible assembly, which can be categorized in the following areas:

- Technoeconomic analysis
- System configuration
- Sensing
- End effector and manipulator
- Planning and sequencing
- Modeling and simulation
- Part storage, feeding and presentation
- Part mating
- Product design

The Automated Flexible Assembly Workcell proposed in this document has an enormous potential as a test bed for the research, implementation, and evaluation of models and techniques developed mainly in the areas of (1) system configuration, (2) sensing, (3) end effector and manipulators, (4) part storage, feeding and presentation, and (5) parts mating. This section will clearly identify this potential through a summary description of these five areas of research, followed by examples of work that is being conducted in each of the respective domains.

3.5.1 - System Configuration

One of key factors for the flexibility of an automated assembly system is related to a proper selection and arrangement of the equipment in the workcell. Modularity of hardware and software, geometry of the assembly workcell, coordination and communication among the elements of the station, real-time control, monitoring of system performance, and error recovery and replanning are some of opportunities for research in the area of system configuration.

Younis and Cavalier of Cleveland State University [26] have developed a zero-one mixed integer programming formulation for the optimal layout and location of a robotic assembly cell based on space constraints. The objective is to minimize a total weighted round-trip travel of the robotic arm among feeders and fixed assembly locations.

Cheng, Poon, and Montor of Concordia University, Canada [27], describe a synchronization control scheme applicable to a robotic assembly cell. Their method aims to ensure rapid rendezvous with accurate tracking of the assembly operations.

3.5.2 - Sensing

In flexible assembly, because of the unstructured environment and because of some degree of uncertainty, there is a need for sensors and machine vision systems. Tasks normally executed by sensing devices and machine vision systems include automated assembly inspection; work cell testing, calibration, and diagnosis; automated part identification; part location and spatial orientation recognition; and end-effector velocity, force, and position measurement. The modeling, design, selection, integration, and signal processing of sensing devices are a few topics for research in this area.

The design and analysis of an electro-optical robotic force and torque sensor by Sun, Benhabib, and Dai of the University of Toronto [28] is an example of investigation in sensing area. This sensor has six degrees of freedom, high sensitivity, and can be used for different force or torque ranges.

Another illustration is a three-dimensional robot vision sensor based on active triangulation and a method using astigmatism is described by Kazuo of Keio University, Japan [29]. The Kazuo method offers a high degree of accuracy in determining the location and orientation of parts.

3.5.3 - End Effector and Manipulator

The flexibility and performance of an assembly process are directly related to the characteristics of the manipulator and the end-effector used. Design, modeling, simulation, and test of mechanical components, control algorithms, and programming languages are some of issues researched in this area.

The development of a robotic end effector that improves the accuracy and repeatability of the robot described by Derby (GRASP Incorporated) is a good example of research in the end-effector and manipulator area [30]. Derby's device allows even inaccurate robots to achieve an accuracy and repeatability of 1/10th of an inch by docking with the work surface.

A whole-sensitive arm manipulator has been investigated by Lumelsky and Cheung of Yale University [30]. The arm manipulator is covered with a sensitive skin sensor to detect nearby objects. The sensing data collected can be used in conjunction with the motion planning algorithms to avoid collisions for the entire robot arm in an unknown or varying environment.

3.5.4 - Part Storage, Feeding, and Presentation

The appropriated presentation of parts to the robot is essential for the success of any assembly. The correct separation, orientation, and presentation of a part are directly related to the design of feeders and part storage devices (such as pallets). The development of flexible, programmable, and high speed feeder systems; expert systems for kitting of incoming parts, and group technology are some topics studied in this area.

A part-feeding system that can feed many different parts by automatically reconfiguring itself in real-time is described by Gordon, Arpriarian, and Christopher (Intelligent Automation Systems) [1]. The system has programmable mechanisms to separate parts, and a two-view, high speed 2D, machine vision system is used to determine the location of the parts.

Another example of research done in this area is a machine vision technique based on the principle of retroflective vision sensing for discrete part-presentation developed by Lee and Li of Georgia Institute of Technology [31]. The technique uses retroflective surfaces to create high object-to-background contrast images, facilitating the recognition of the location and orientation of a part.

3.5.5 - Part Mating

Part mating is a key element in flexible assembly, since assembly is also considered a geometric problem. Research issues are related to position, orientation and forces during the assembly of parts. Insertion methods based on compliance and vibration, creation of models to ensure the compatibility of tolerances on mating parts with the precision of the assembly robot, analysis of force and torque reaction during assembly, and peg-in-hole analysis are common topics researched in the mating area.

An example of research in part mating, conducted by Caine of Massachusetts Institute of Technology [32], is the analysis of the impact of chamfers' degree of curvature and location on the peg-tip on the reliability of the part insertion operation.

The modeling and parameter analysis of vibration assisted robotic peg-in-hole insertion conducted by Leu and Liu of New Jersey Institute of Technology [33], is another example of work done is this area. Their study aims to solve insertion failure due to insufficient assembly forces, robot deflection, and assembly geometry restriction.

4 - METHODOLOGY

4.1 - INTRODUCTION

The Manufacturing, Automation and Robotics Laboratory (MARL) in the Department of Industrial and Systems Engineering at Virginia Polytechnic Institute and State University is being created to house an integrated and automated manufacturing system for the purpose of both applied and basic research. The laboratory will include an automatic storage and retrieval system, a flexible manufacturing system, an automated flexible assembly cell, and other systems dedicated to specific research. These systems will be integrated physically, through an automated guided vehicle (AGV) system, and electronically, by way of one or more RS-232-C or local area networks.

The objective of this project was to design and implement the basic system of the automated flexible assembly cell. Mechanical integration, electrical interconnecting, and communication software among the cell components were designed and implemented. Additionally, basic cell control software was provided. General purpose components are available: robots, transfer mechanisms, sensors, and a cell control computer. Means were provided for the future addition of assembly fixtures, feeders, end effectors, and other dedicated devices that might be needed for specific applications.

The design and implementation was accomplished in four consecutive stages:

a) Configuration and layout

b) Control, monitoring, and communication hardware

c) Control, monitoring, and communication software

d) Testing and demonstration software

The design and implementation were steered by (1) the requirements of the research areas (2) the Manufacturing, Automation and Robotic Laboratory requirements, (3) equipment available, and (4) guidelines defined for the assembly cell.

4.2 - REQUIREMENTS

The requirements for the assembly cell were divided into three levels: (1) Manufacturing, Automation and Robotic Laboratory (MARL), (2) research areas, and (3) assembly cell.

4.2.1 - Manufacturing, Automation and Robotic Laboratory

The major requirements associated with the laboratory were related to physical location of the assembly cell and the integration of the cell with other systems. The basic design of the laboratory established a work area for the flexible assembly cell as indicated in Figure 4.1. The integration of the assembly cell with other systems required standardization of interfaces for material flow and data interchange among the systems in the MARL. The material integration (load and unload) would be carried out by an Automated Guided Vehicle (AGV) System. Dedicated pallets would be used to transfer

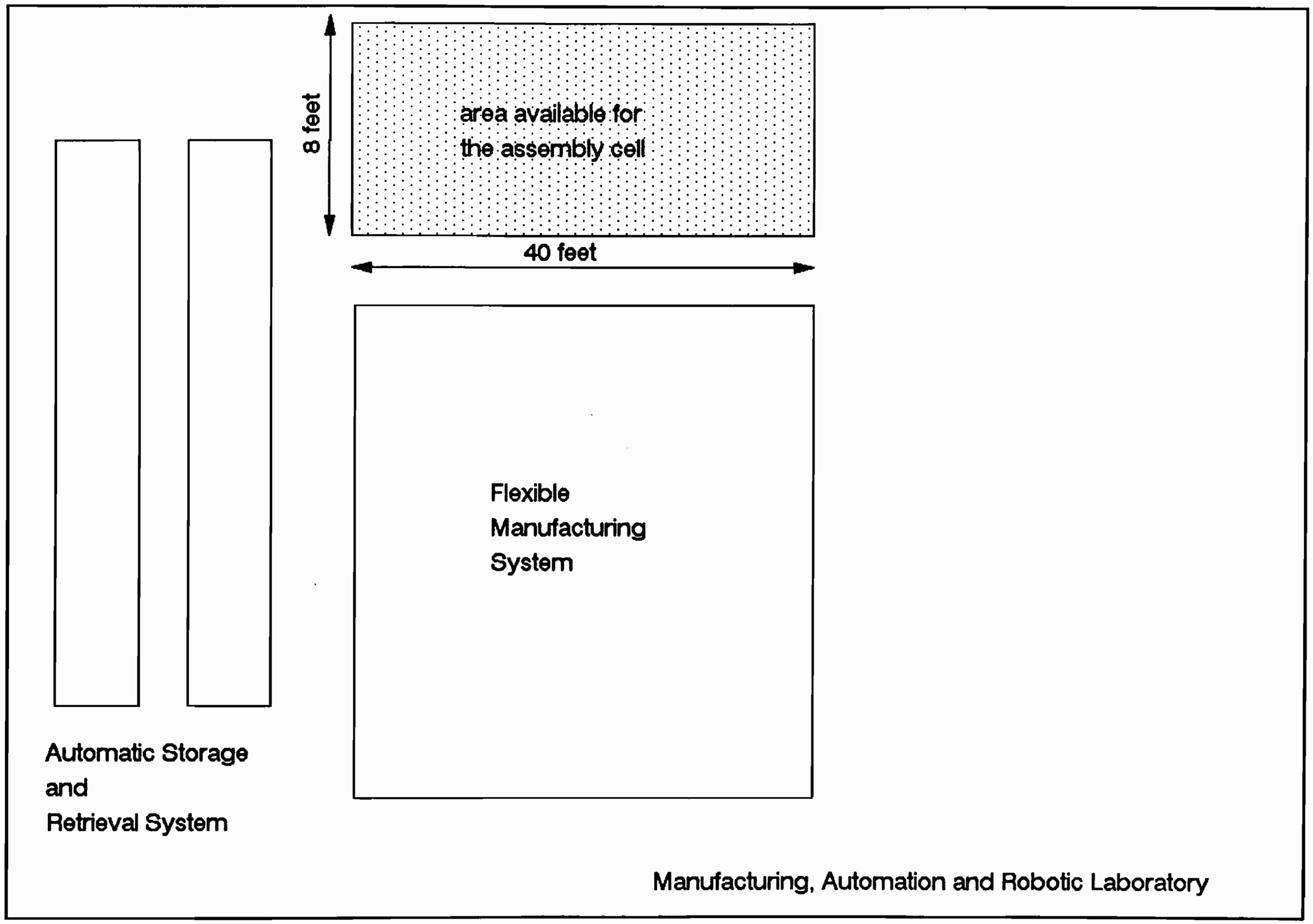


Figure 4.1 - Area Available for the Assembly Cell in the MARL

the parts and tools among the MARL systems. The data integration in the MARL would be accomplished via serial interfaces RS-232-C and/or one or more local area networks (LAN).

4.2.2 - Research Areas

The requirements for the research areas were associated with future integration of investigation-related devices in the assembly cell. The needs were basically free physical space inside and outside the robots' work envelope for placement of devices; access to electrical power; electrical interfaces for command, status, and data; and compressed air. A list of some possible requirements for each research area is shown in Table 4.1.

4.2.3 - Assembly Cell

Guidelines were defined for operation, safety, and maintenance of the assembly cell. The robot, cell controller, and conveyor modules should be modular, self-contained, and controlled by their own microprocessor for easy reconfiguration and expansion of the cell. Each module should be operated independently or integrated into the assembly cell. Direct and real-time communication among the sub-systems was desired. The integration of the sub-subsystem and the coordination of the cell should be accomplished by a cell control computer.

Safety measures needed to be provided for the assembly cell, including physical and electronic barriers, alert signals and lights, and fast stop emergency devices. Also reasonable free spaces inside and outside the work envelope of the manipulators should be available for installation, operation, and maintenance of present and future devices in the

Table 4.1 - Research Areas Requirements

Research Area	**Requirements**
System Configuration	- devices with modular hardware and standard bus* - programmable devices* - devices with serial interface**
Sensing	- robot with discrete input/output ports* - space inside/outside robot's work envelope* - processing software** - devices with modular hardware and standard bus** - analog input/output ports**
End Effectors and Manipulators	- robot with discrete input/output ports* - space inside/outside robot's work envelope* - manipulator permitting end-effector interchanger* - devices with modular hardware and standard bus** - analog input/output ports**
Part Storage, Feeding, and Presentation	- devices with discrete input/output ports* - space inside/outside robot's work envelope* - devices with modular hardware and standard bus**
Parts Mating	- devices with discrete input/output ports* - space inside robot's work envelope*

* basic requirements

** desirable requirements

cell.

4.3 - EQUIPMENT AVAILABLE

Several components were available for consideration for use in the assembly cell: six robot systems, a transfer mechanism, parts presence detection sensors, a number of programmable logic controllers (PLCs), and several computers.

4.3.1 - Robots

Six robots (manipulator and controller) were in four different models were available. The manipulators have two distinct geometric configurations, with four or six degrees of freedom. A summary list of the robots available is shown in Table 4.2.

For this project the three SCARA type robot systems were selected, since the horizontally-joined articulation and the selective compliance feature of the SCARA robot makes it the most suitable and utilized manipulator for assembly tasks [34]. Other important features considered during the selection process were the availability of three identical systems and the hardware and software characteristics of the Automatix controllers [35, 36], summarized in Table 4.3.

4.3.2 - Transfer Mechanism

A modular (adjustable length and height), chain-driven conveyor was available. Associated with the conveyor were several lift devices, roller lift-and-transfer devices,

Table 4.2 - List of Available Robots

quantity	**geometric configuration**	**degrees of freedom**	**work envelope**	**model**
1	polar	6	spherical	General Electric - GP66
1	jointed-arm horizontal-axes	6	spherical	America Robot - Merlin
1	jointed-arm	4	spherical	General Electric - P50
3	jointed-arm (SCARA)	4	cylindrical	Automatix AI-32 robot vertical-axes AI-360 controller

Table 4.3 - Main Characteristics of the Automatix Robot Controllers

- Powerful programming language (RAIL)
- Motion simulation
- Continuous monitoring of external signals during the robot motion
- 48-input and 48-output discrete ports
- Teach pendant
- Three serial ports, with resident communication software
- User interfaces (keyboard, monitor)
- Storage devices (floppy drives)
- VME bus backplane with modular boards

chain driving motors, and photosensors.

4.3.3 - Programmable Logic Controller (PLC)

The programmable logic controllers TI520/530 series, TI405 series, GE series 3, and GE series 6 were available for consideration for use in the assembly cell. The model selected was the TI435 from Texas Instruments Series TI405 [37] because of its low cost, powerful internal set of functions, excellent programming and debugging language, and compact dimensions. The same PLC was defined as the standard model for other systems in the Manufacturing, Automation and Robotic Laboratory.

The TI435 contains a CPU module and several digital input and output modules. These modules are interconnected by a multiple connector backplane bus, easing future reconfiguration and expansion of the PLC. Two serial ports are available on the CPU module: Programming and Interfacing. The Programming Serial Port permits the editing and debugging of the Relay Ladder Programs, by way of a dedicated Machine Interface Unit (MIU), or an IBM-PC or compatible, using the TISoft Software [38]. The interfacing port (Serial Interface Port) permits remote access to internal functions and memory contents of the PLC, employing the user's customized software. This feature allows remote on-line control and monitoring of programs running in the PLC.

4.3.4 - Cell Control Computer

IBM microcomputers model 7541, PS/2 - 30, and 7552 were accessible in the Manufacturing, Automation and Robotic Laboratory to be used as cell controller. Because the IBM 7552 is an industrial computer designed to operate on the plant floor, has modular configuration, and can be rack mounted, it was selected to be the assembly cell controller [39]. The same computer model will be used to control the operation of other system in the MARL. Along with the standard components (keyboard, monitor, hard disk, and memory), a real-time co-processor (RIC) card, Multiport/2, was added to this computer. The RIC card has is own microprocessor, memory bank, and interfacing drives to execute real-time communication with up to eight external serial devices [40].

5 - CONFIGURATION AND LAYOUT

A mixed configuration, assembly line - single station, with two stations was chosen for the assembly cell (Figures 5.1 and 5.2). One station (#1) has one robot, and the other station (#2) contains two robots with overlapping work envelopes. This arrangement allows several different assembly sequences: single station - single robot, single station - multiple robots, and assembly line with single and multiple robots per station. The overlapping at Station #2 suggests several additional opportunities for research, such as real-time multiprocessing control, collision prevention sensing, multiple-arm part handling, and several others.

The conveyor system is used to physical integration of the stations. Since the cell can be operated as an assembly line and can be loaded and unloaded by automated guided vehicles, buffers to control the flow of material are desired between the stations, and between the stations and the AGVs. The alternative selected to implement the flow control buffers was a closed loop conveyor configuration, as shown in Figure 5.3. Additionally, to keep the pallets in pre-defined positions and to permit both robots at station #2 to work simultaneously with parts present, a pallet, lift devices, and two spurs were added to the conveyor. With this configuration, each robot can reach a part in two points on the conveyor: in its main-conveyor lift (Robot Lift) and in its spur (Robot Dock). Lift-and-transfer devices are available to transfer pallets between the spurs and the main conveyor. Photosensors are assembled in the lift, lift-and-transfer, and elevator devices, to monitor the actual position of the parts on the conveyor.

Due to space constraints and the availability of two elevators, the closed loop conveyor system is a double-level system. The top and bottom subsets are interconnected

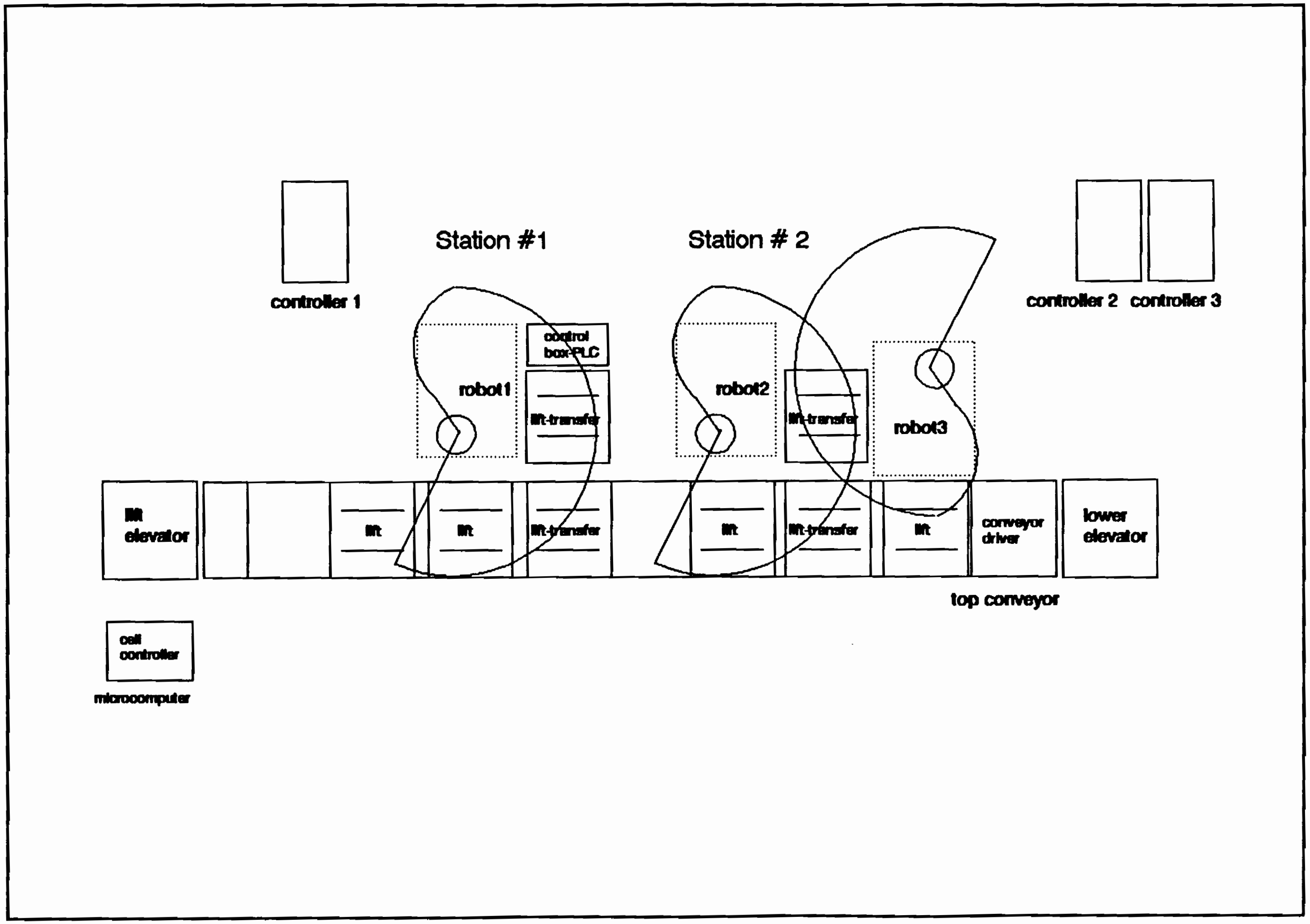


Figure 5.1 - Assembly Cell Configuration

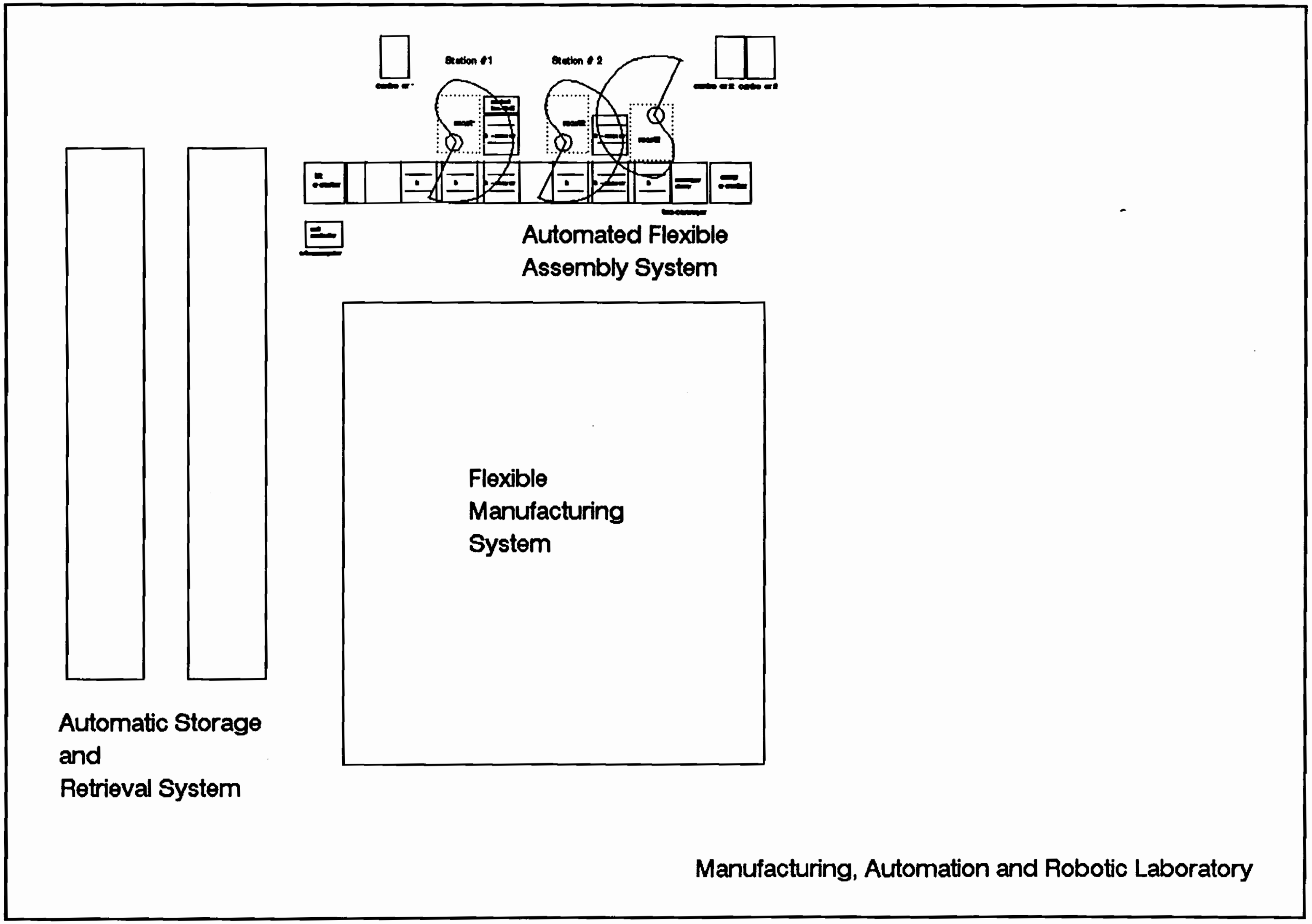


Figure 5.2 - Assembly Cell Location in the MARL

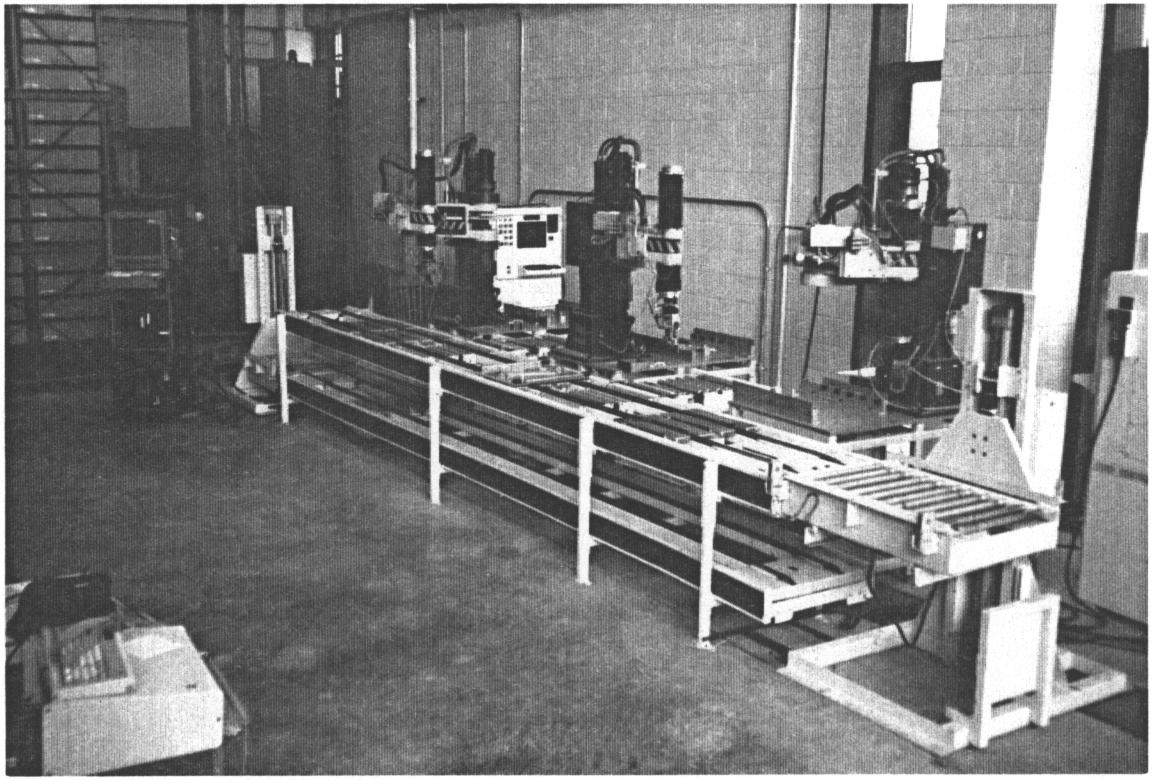


Figure 5.3 - Assembly Cell Layout

by way of elevators located at both extremities of the conveyor. Because of technical constraints, the top and bottom conveyor subsets are unidirectional. The top chain runs from the station #1 to station #2 (from the lift to lower elevator) direction, and the bottom subset runs in the opposite direction, as show in Figure 5.4.

The robots are anchored on the top of metallic tables. Most of the area on top of the tables is free space and can be reached by the robots, permitting future installation of research-related devices inside the robots' work envelopes.

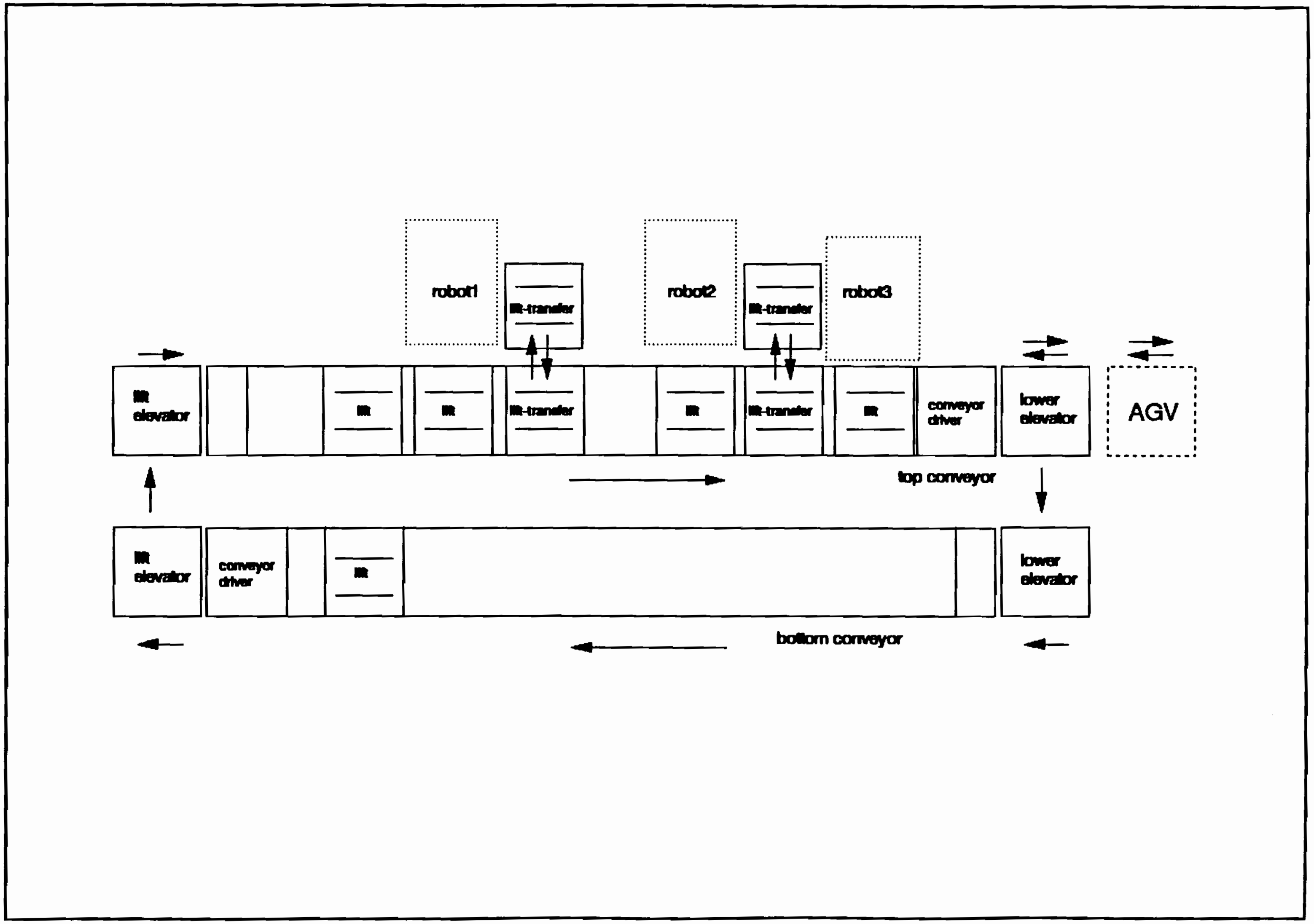


Figure 5.4 - Material Flow in the Assembly Cell

6 - CONTROL, MONITORING, AND COMMUNICATION HARDWARE

After the implementation of the cell layout, electrical interconnections among the robots, conveyor, and cell controller for data communication, and between the programmable logic controller and the conveyor's devices for command and status, were designed and implemented. Since controllers of the robots have customized firmware to command and monitor the operation of the manipulators, no additional hardware is required to operate the robots.

6.1 - COMMUNICATION

The data integration among the various systems of the Manufacturing, Automation and Robotic Laboratory will be accomplished through RS-232-C interfaces and/or local area networks (LANs). The assembly cell controller will carry out the interfacing between the components in the cell and the other systems in the MARL. The cell controller computer has nine RS-232-C interfaces available; four are utilized for internal communication in the cell, and the other five are available for both external and internal cell communications. The modular configuration of the industrial computer permits the inclusion of either Local Area Network card(s) and/or additional RS-232-C communication interfaces.

For data integration into the cell, direct communication among the PLC, robots, and conveyor are implemented (see Figure 6.1). Serial interfaces RS-232-C are employed for communication between the cell controller and the robots, and the cell controller and the conveyor. Discrete I/O ports are used for communication between the robots and conveyor.

The cell control computer has a plug-in Realtime Interface Co-Processor (RIC) Card, model Multiport/2 [41]. This card has eight independent serial ports. Each port can be programmed and operated individually in either half-duplex or full-duplex mode. The co-processor card has a built-in 80816 microprocessor and 512K of Random Access Memory (RAM) to perform on-board processing and data storage, providing serial communication without degrading the performance of the of host microcomputer. Four ports of the card have been used. Port 1 is connected to the Serial Interface Port of the PLC. The RIC's port 2 is associated with port 1 of robot 1, and port 3 of the co-processor is tied to port 1 of robot 2. The port 4 of the RIC card is reserved for robot 3. A Distribution Box containing eight DB-25 male connectors are available for the external access to the Realtime Co-Processor Card, as shown in Figure 6.2. The serial cables built for the communication RIC-robots and RIC-PLC are show in Figure 6.1.

The communication between the conveyor and robots 1 and 2 is established using discrete ports of the PLC and the robot controllers. The input ports 'X0' through 'X10' and output ports 'Y0' through 'Y10' of the PLC are connected to input ports 'INPORT17' through 'INPORT24', and output ports 'OUTPORT17' through 'OUTPORT24' of the controller1, respectively. Similarly, the PLC's ports 'X10' through 'X17', and 'Y10' through 'Y17' are connected to input ports 'INPORT17' through 'INPORT24' and output ports 'OUTPORT17' through 'OUTPORT24' of the controller 2. The logical levels for the communication are 0V - 24V DC, where 0V is equivalent to the level logic zero, and 24V DC is considered the level logic one.

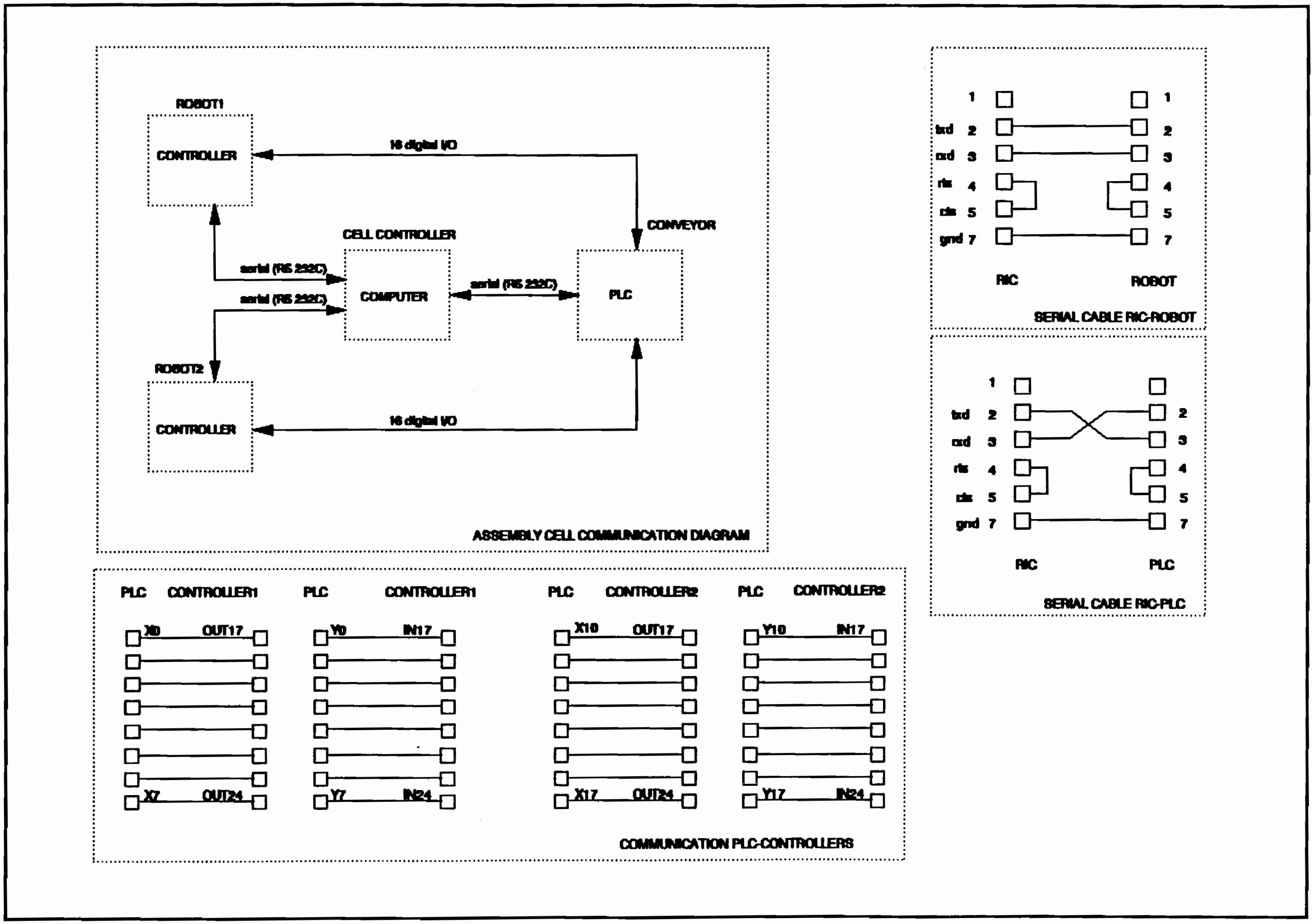


Figure 6.1 - Communication Interfaces in the Assembly Cell

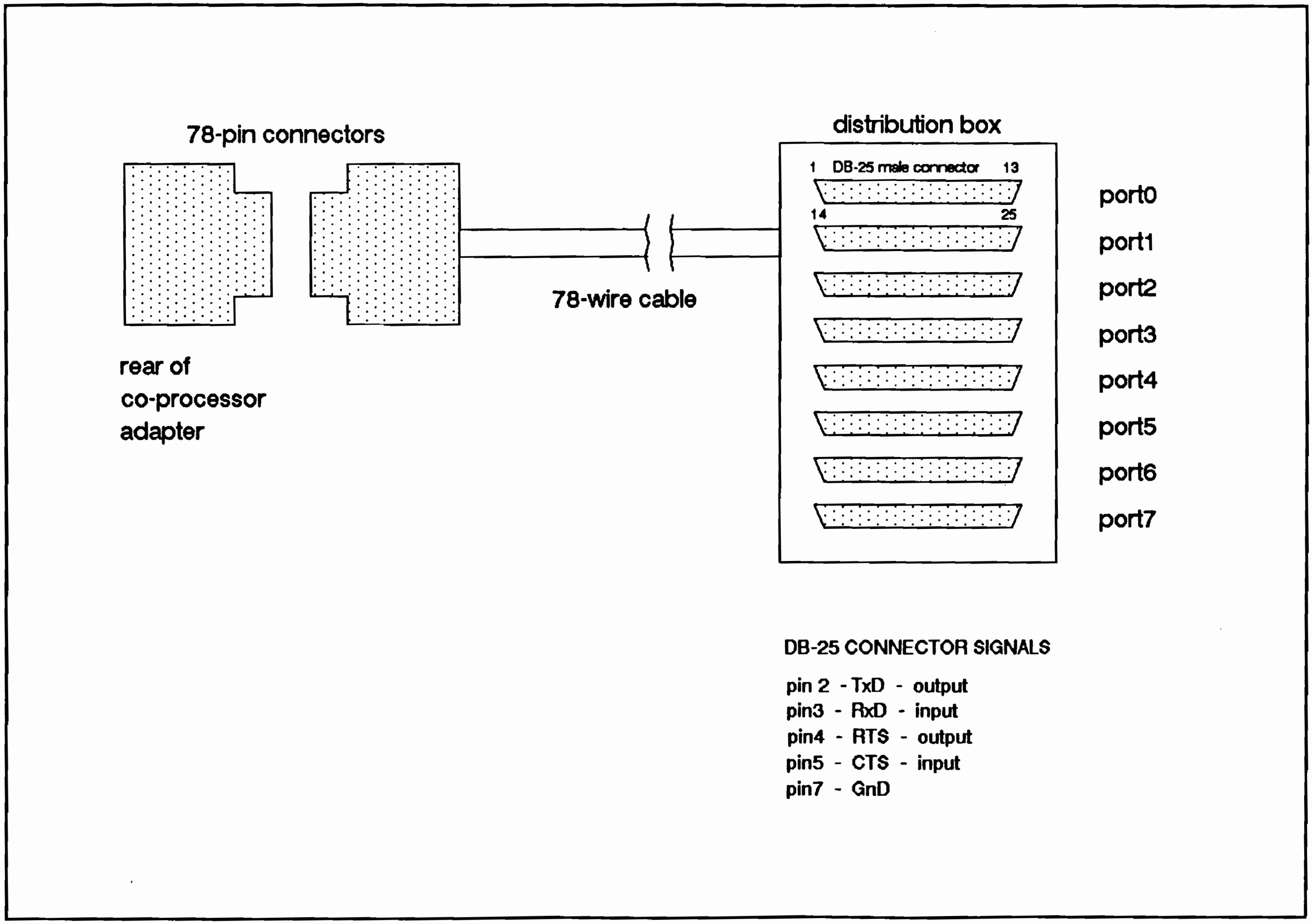


Figure 6.2 - Distribution Box of the Realtime Co-Processor Card

6.2 - COMMAND AND CONTROL OF THE CONVEYOR

The Programmable Logic Controller is responsible for the control of all operations of the conveyor. To control the flow of pallets, the PLC monitors the location and directs the motion of pallets on the conveyor. Proximity sensors are read by the PLC to detect the present position of the pallets. Actuating over the motors and electro-pneumatic valves of the lift, lift-and-transfer, elevators, and chain drive devices, the programmable controller can dictate the path to be followed by the pallets.

For each sensor, motor, and electro-pneumatic valve, there are one or more associated input or output ports of the PLC. Tables 6.1A and 6.1B list the ports associated with each device of the conveyor. Sensors and valves are connected directly to the PLC; however, the electrical motors require high voltage and current that cannot be switched directly by the output ports of the PLC. For these motors, dedicated interfaces were implemented. A more detailed explanation of the interfacing PLC-conveyor is described in the following sub-sections.

6.2.1 - Sensors

The sensors are photoelectric proximity devices, which respond to changes in the intensity. The model available is a OMRON E3S-DS5 photoelectric switch. It has an invisible infrared Light Emitting Diode (LED) and a phototransistor. When an object is near the sensor, the light emitted by the LED reflects on the surface of the object and it is detected by the phototransistor. Since the phototransistor is only sensitive to infrared light, the ambient illumination does not have any influence on the performance of the

Table 6.1A - Command and Status PLC I/O List

Device	Location	I/O	PLC's Port
sensor1	top limit lift elevator	in	X20
sensor2	bottom limit lift elevator	in	X21
sensor3	roller lift elevator	in	X22
sensor4	beginning top conveyor lift	in	X23
sensor5	robot1 lift	in	X24
sensor6	robot1 conveyor lift-transfer	in	X25
sensor7	robot1 dock lift-transfer	in	X26
sensor8	robot2 lift	in	X27
sensor9	robot2 conveyor lift-transfer	in	X30
sensor10	robot2 dock lift-transfer	in	X31
sensor11	end top conveyor lift	in	X32
sensor12	top limit lower elevator	in	X33
sensor13	bottom limit lower elevator	in	X34
sensor14	roller lower elevator	in	X35
sensor15	end bottom conveyor lift	in	X36
motor1	lift elevator-roller on/off	out	Y20
motor2	lift elevator-roller direction	out	Y21
motor3	robot1 conveyor L-T roller on/off	out	Y22
motor4	robot1 conveyor L-T roller dir.	out	Y23
motor5	robot1 dock L-T roller on/off	out	Y24
motor6	robot1 dock L-T roller direction	out	Y25
motor7	robot2 conveyor L-T roller on/off	out	Y26
motor8	robot2 conveyor L-T roller dir.	out	Y27
motor9	robot2 dock L-T roller on/off	out	Y30
motor10	robot2 dock L-T roller direction	out	Y31
motor11	lower elevator-roller on/off	out	Y32
motor12	lower elevator-roller direction	out	Y33
motor13	top conveyor driver	out	Y34
motor14	bottom conveyor driver	out	Y35

Table 6.1B - Command and Status PLC I/O List

Device	Location	i/o	PLC's Port
valve1	lower elevator lift	out	Y40
valve2	lower elevator lower	out	Y41
valve3	beginning top conveyor lift	out	Y42
valve4	robot1 lift	out	Y43
valve5	robot1 conveyor lift-transfer	out	Y44
valve6	robot1 dock lift-transfer	out	Y45
valve7	robot2 lift	out	Y46
valve8	robot2 conveyor lift-transfer	out	Y47
valve9	robot2 dock lift-transfer	out	Y50
valve10	end top conveyor lift	out	Y51
valve11	lift elevator lift	out	Y52
valve12	lift elevator lower	out	Y53
valve13	end bottom conveyor lift	out	Y54
e-stop1	emergency stop switch	in	Y40
e-stop2	emergency stop command	out	Y36

sensor. A large range of types of materials can be detected by this sensor including translucent pallets. The sensitivity of the sensors can be adjusted through a built-in variable resistor.

The output of the sensor is a binary signal. When a part is near the sensor, its output assumes level logic zero or 0V; otherwise the output stays in level logic one or 12-24V DC. The sensor has three wires: RED for power supply (12-24V DC), BLACK for signal and power supply references (0V), and WHITE for output signal.

Since the current required by the PLC is larger than that one supplied by the sensor, a 'pull-up' resistor of 1.5K Ohm is connected to each PLC input. The schematic of the interconnections PLC-sensors is shown in Figure 6.3.

6.2.2 - Lift Devices

The Lift devices are flat metallic sheets that usually stay below the conveyor chain level, and rise to a level higher than the conveyor when activated by an electro-pneumatic valve. The valve opens when energized, allowing the compressed air flow into a lift cylinder. It stays in the lift position until the electrical voltage is removed, when the valve closes, cutting the air flow and releasing the compressed air from the cylinder.

The PLC utilizes a 16-point Solid State Relay module (U-O5T) to command the 110V AC electro-pneumatic valves of the Lift devices (shown in Figure 6.4).

6.2.3 - Lift-and-Transfer Devices

The Lift-and-Transfer devices are composed of a lift module and a motor-driven bi-directional transfer module. The lift module is identical to the Lift device described in

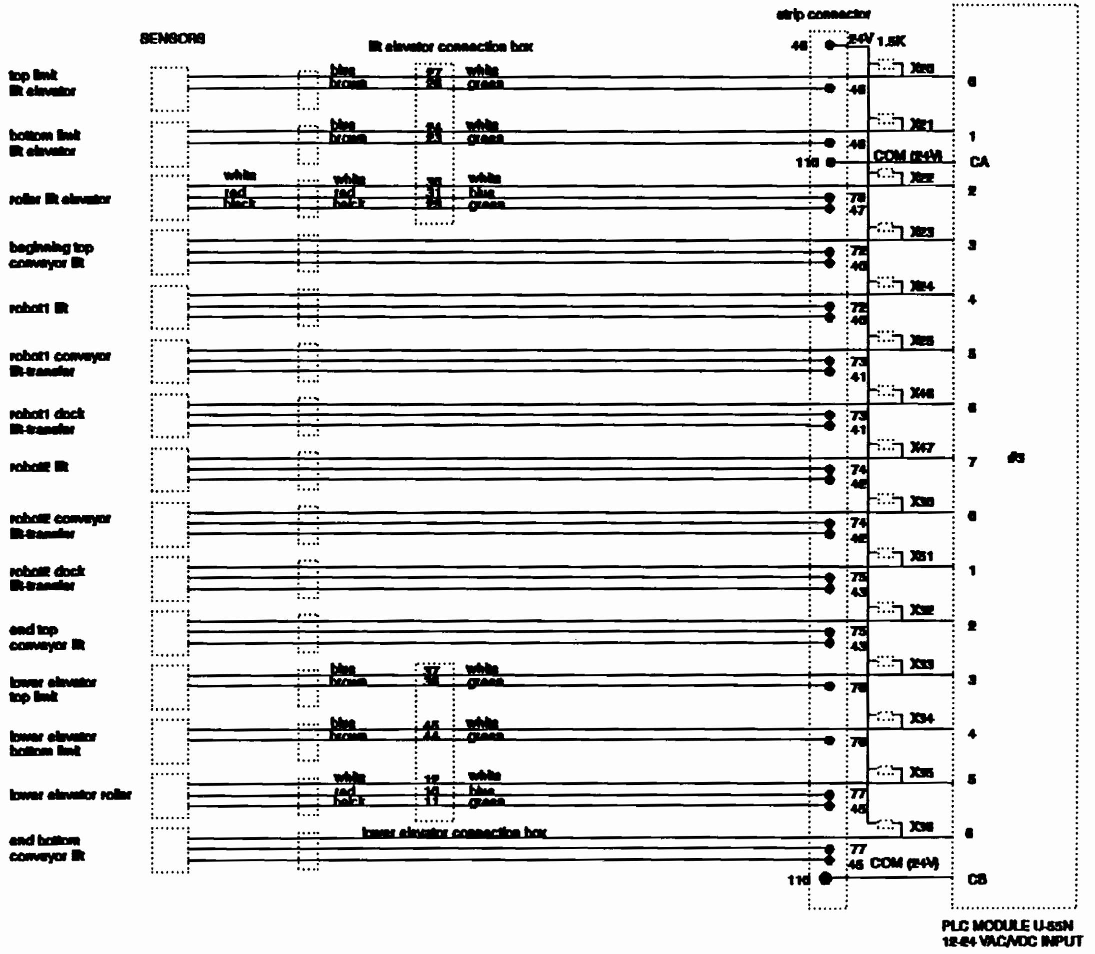


Figure 6.3 - PLC-Photosensor Interfacing

the previous section. The transfer module is composed of a set of rollers activated by an electrical monophase alternating current (AC) motor. The direction of rotation of the rollers is defined by which of the two motor's input wires (red or blue) is energized.

Dedicated drive circuits were implemented to energize and set the rotation direction of the motors by the PLC, as shown in Figure 6.5. The electro-mechanical relays (#1 through #6) are used to select the rotation direction, and solid-state relays (#1 through #6) are used to turn ON and OFF the motors. Fuses are included in the circuitry to protect the relays and the motors. In order to control a Lift-and-Transfer device, three PLC outputs are required: (1) lift up and down, (2) roller direction, and (3) roller rotation (as shown in Tables 6.1A and 6.1B).

6.2.4 - Conveyor Drive Motors

The conveyor chains are pulled by three-phase alternating current electrical motors. Individual motors are used for the top and bottom conveyors. Three-contact electro-mechanical contactors, commanded by the PLC, activate these motors, as shown the Figure 6.6. Fuses (#7 through #12) are used to protect the motors and the contactors.

6.3.5 - Control Box

A self-contained control box is used to house the PLC, the 24V DC power supply, the driving relays for the conveyor, the contactors, and interconnecting strips. The objective of the box is to provide mechanical support for the installation of the components, component protection, and the isolation of the high voltage circuits (for safety). Additional space is available for future inclusion of other devices. The internal

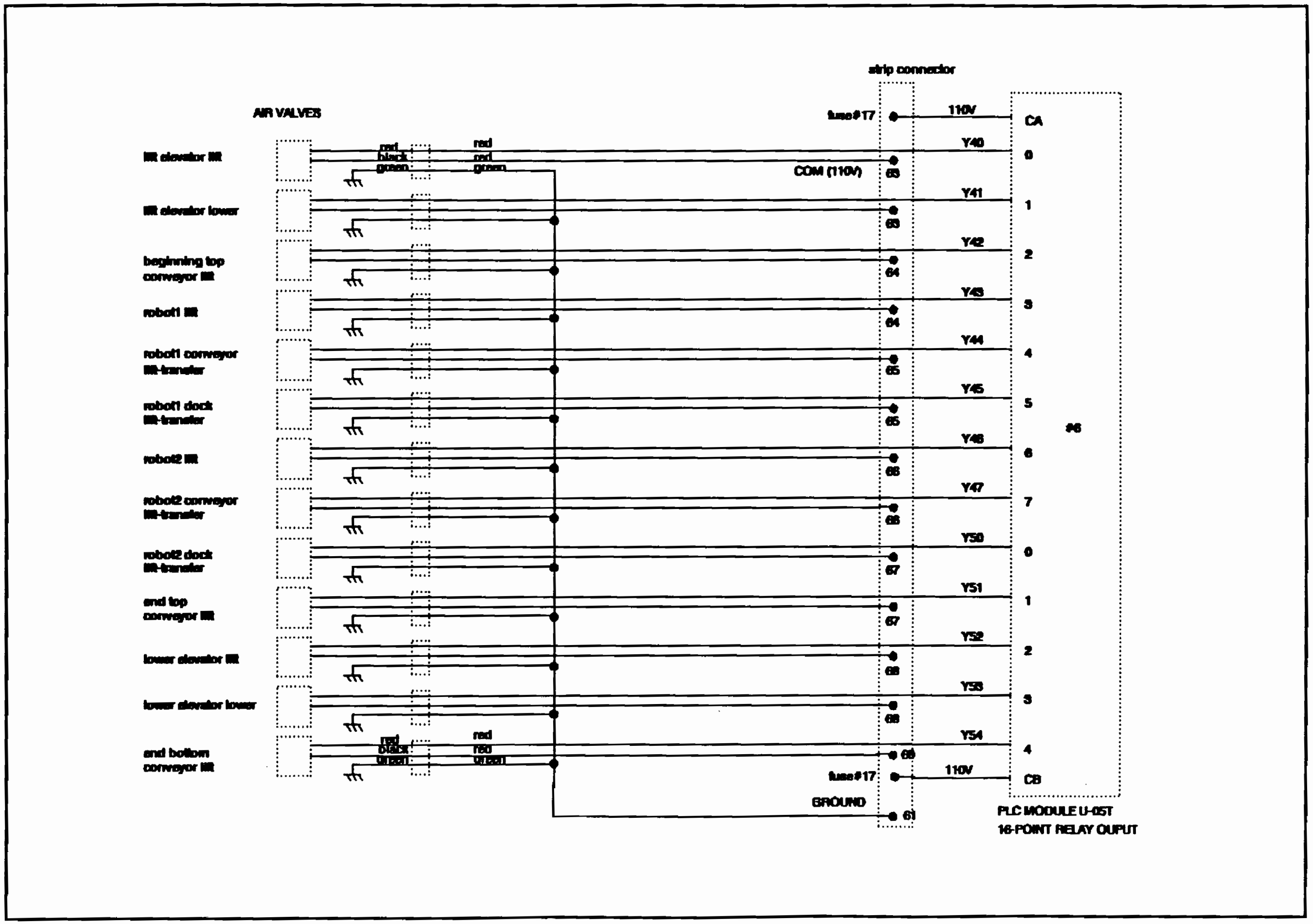


Figure 6.4 - PLC-Lift Device Interfacing

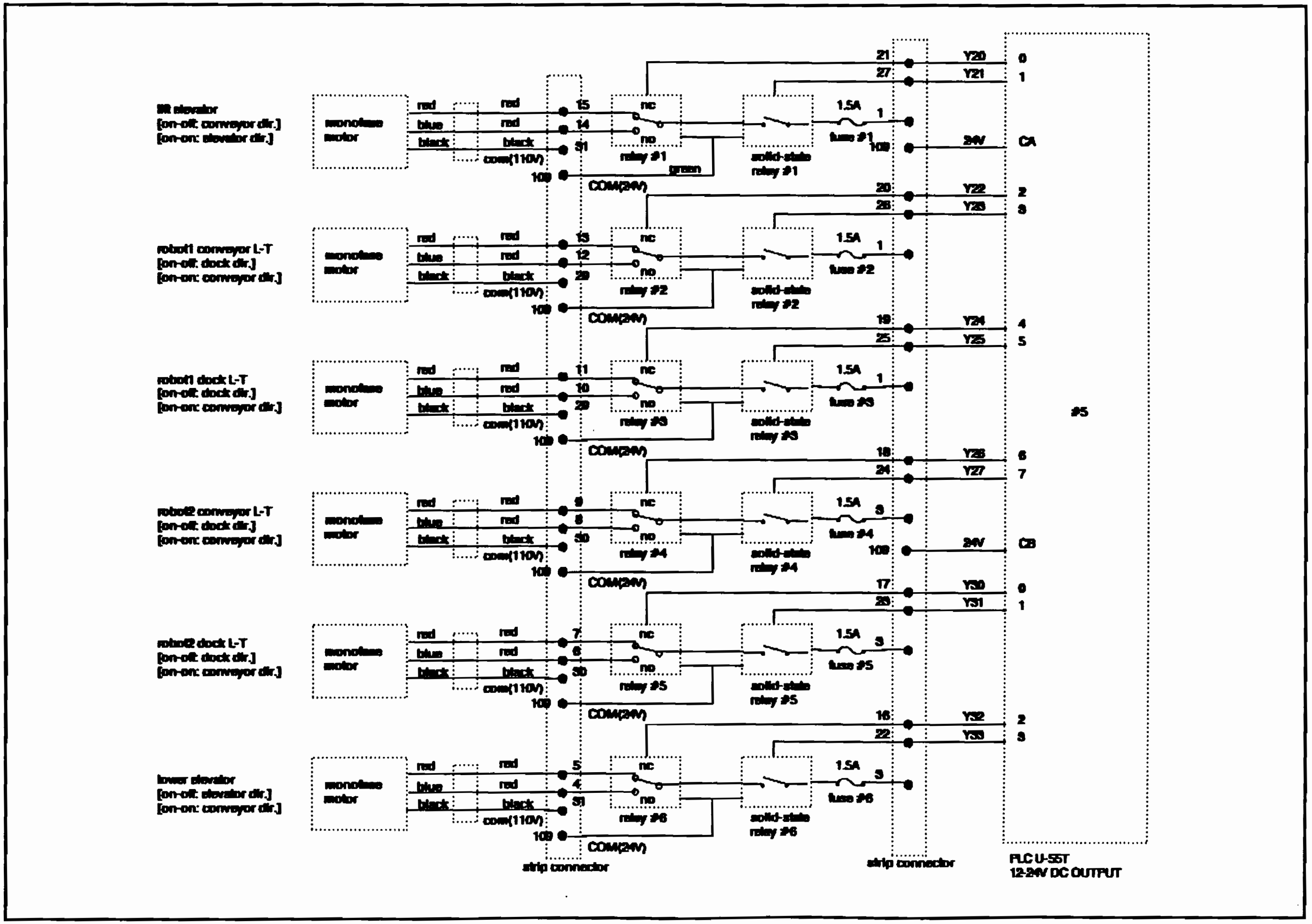


Figure 6.5 - PLC - Lift-and-Transfer Device Interfacing

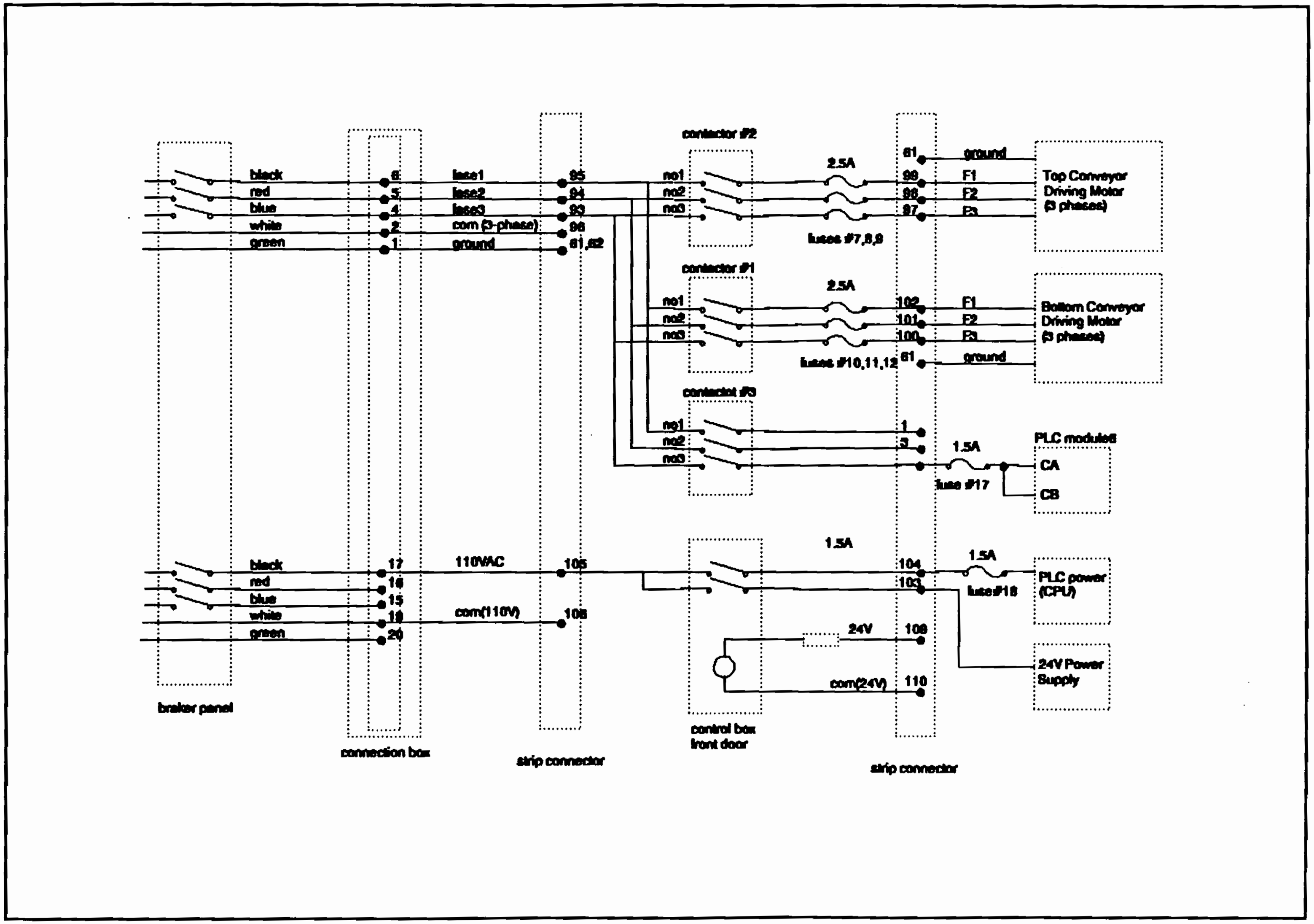


Figure 6.6 - PLC - Chain Drive Motor Interfacing

layout of the control box is show in the Figure 6.7, and the strip connectors wiring is listed Tables 6.2A, 6.2B, and 6.2C. A switch is provided on the door of the control box to energize the PLC and 24V power supply.

6.3.6 - Electrical Power and Emergency Stop

Six monophase electrical circuits are available for the conveyor (see Figure 6.6). Three are used for the motors and electro-pneumatic valves. A fourth is used for the PLC and 24V DC power supply. Two other circuits are available for future expansion.

The circuits originate from a breaker panel (switches 2, 4, 6, 32, 34, and 36), located between the assembly cell in the automatic storage and retrieval system, pass to a connecting box, and then to contactors inside the control box.

An emergency stop circuit was implemented for the cell. The emergency stop relays of the robots, conveyor, and User Terminal are serially interconnected, as shown in Figure 6.8. If an emergency condition occurs in any of these devices, the entire cell will be disabled. To start the operation of the cell, or restart after an emergency stop (1) remove the emergency stop cause, and then (2) pull the Enable button. To operate individual components in the cell, it is necessary to bypass the cell emergency stop circuit, by keeping the ENABLE button pulled. This procedure does not disable the internal emergency stop circuit of any of the cell devices.

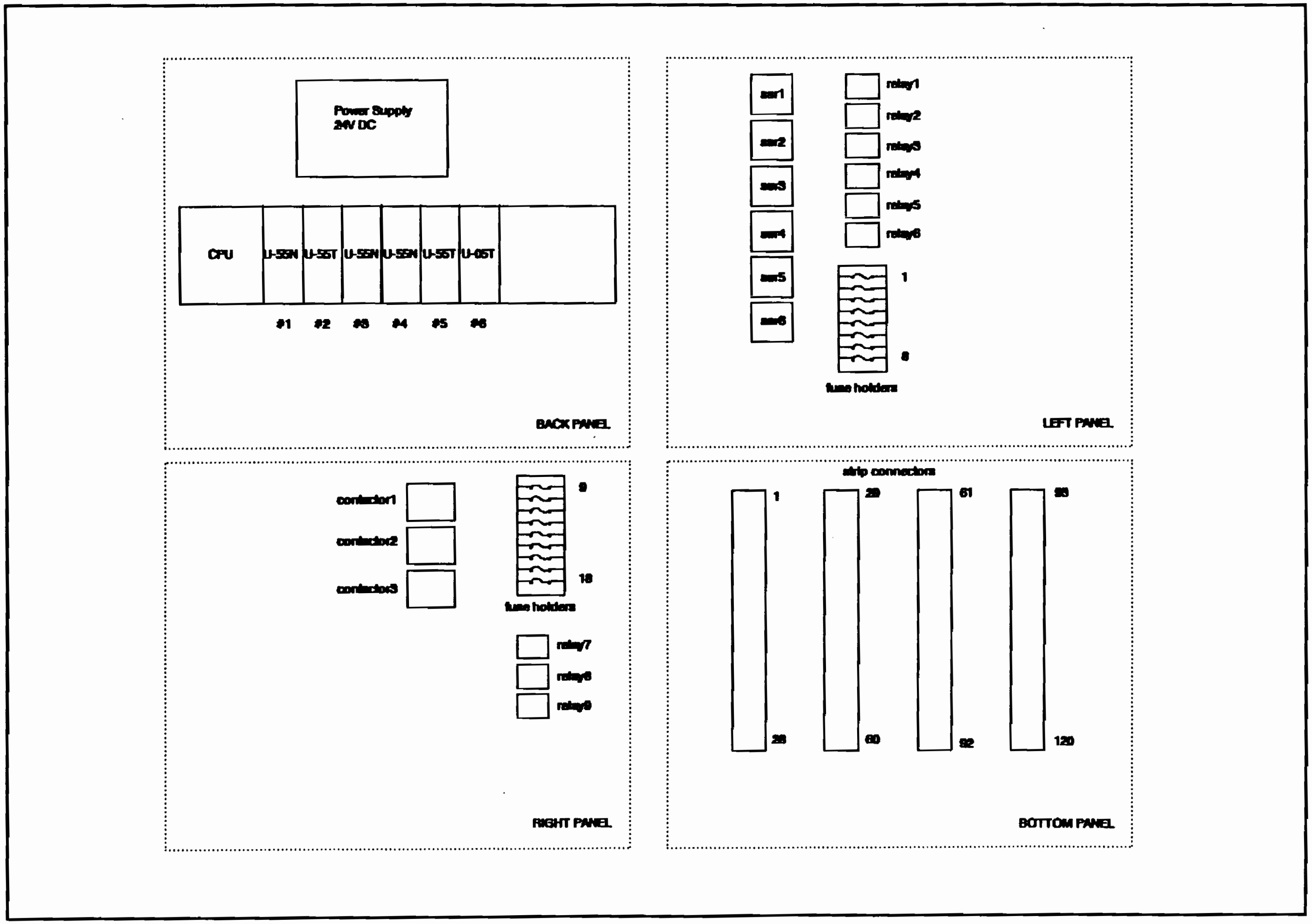


Figure 6.7 - Control Box Layout

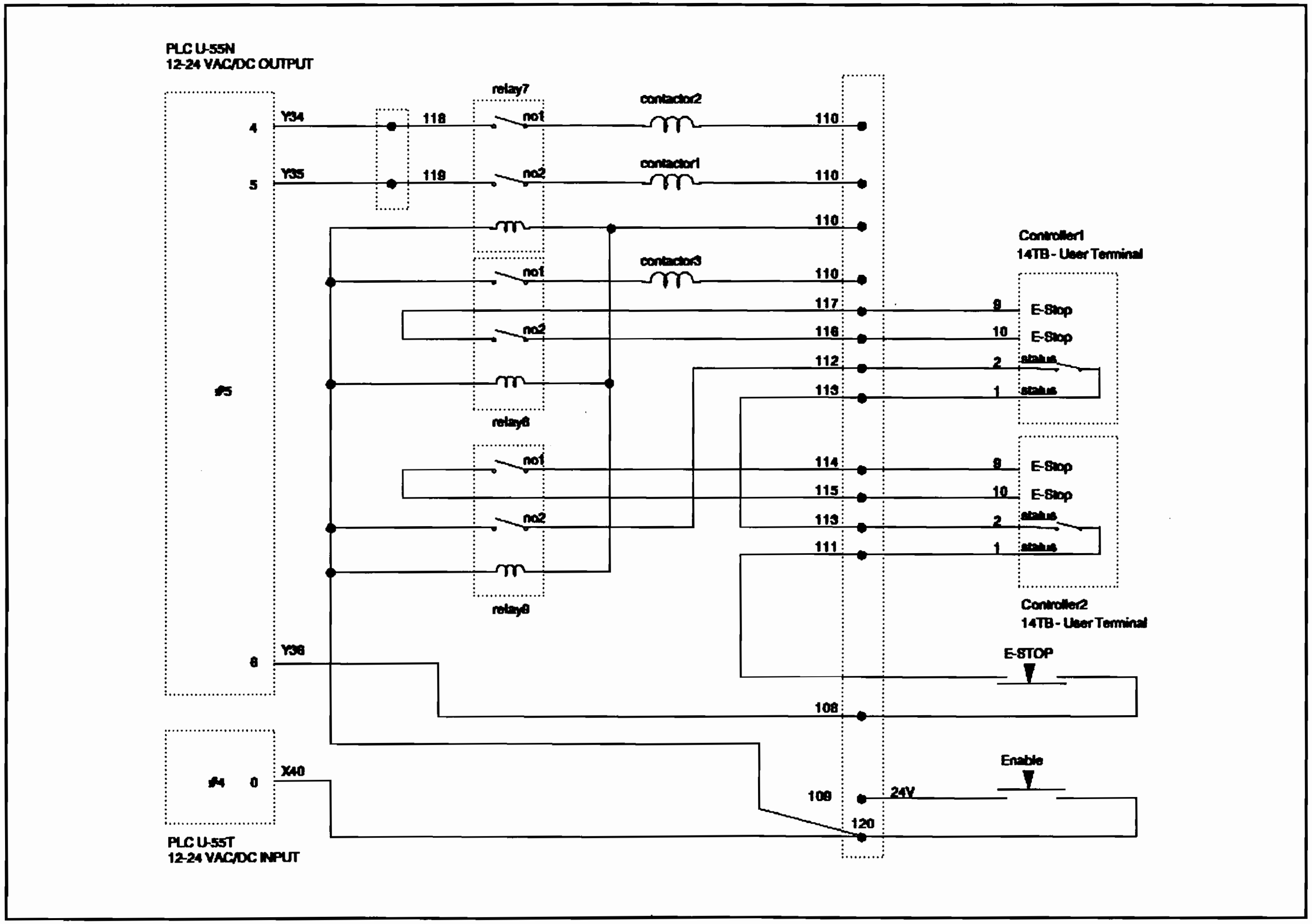


Figure 6.8 - Emergency Stop Circuit

Table 6.2A - Control Box Strip Connectors

Description	**Location**	**Description**
fuses 1,2,3	1	contactor3 no1
	2	
fuses 4,5,6	3	contactor3 no2
relay6 no	4	lift elevator motor
relay6 nc	5	lift elevator motor
relay5 no	6	robot2 dock L-T motor
relay5 nc	7	robot2 dock L-T motor
relay4 no	8	robot2 conveyor L-T motor
relay4 nc	9	robot2 conveyor L-T motor
relay3 no	10	robot1 dock L-T motor
relay3 nc	11	robot1 dock L-T motor
relay2 no	12	robot1 conveyor L-T motor
relay2 nc	13	robot1 conveyor L-T motor
relay1 no	14	lower elevator motor
relay1 nc	15	lower elevator motor
relay 6 coil	16	PLC - Y33
relay 5 coil	17	PLC - Y31
relay 4 coil	18	PLC - Y27
relay 3 coil	19	PLC - Y25
relay 2 coil	20	PLC - Y23
relay 1 coil	21	PLC - Y21
SSR 6	22	PLC - Y32
SSR 5	23	PLC - Y30
SSR 4	24	PLC - Y26
SSR 3	25	PLC - Y24
SSR 2	26	PLC - Y22
SSR 1	27	PLC - Y20
com(24V)	28	loc. 110
com(110V) motor (rollers)	29	loc 96
com(110V) motor (rollers)	30	loc 96
com(110V) motor (rollers)	31	loc 96
	32	
	33	
	34	
	35	
	36	
	37	
	38	
	39	
com(24V)	40	loc 109
com(24V)	41	loc 109

Table 6.2B - Control Box Strip Connectors

Description	Location	Description
com(24V)	42	loc 109
com(24V)	43	loc 109
com(24V)	44	loc 109
com(24V)	45	loc 109
com(24V)	46	loc 109
	47	
	48	
	49	
	50	
	51	
	52	
	53	
	54	
	55	
	56	
	57	
	58	
	59	
	60	
conveyor devices	61	ground
control box	62	ground
com(110V) air valves	63	loc 96
com(110V) air valves	64	loc 96
com(110V) air valves	65	loc 96
com(110V) air valves	66	loc 96
com(110V) air valves	67	loc 96
com(110V) air valves	68	loc 96
com(110V) air valves	69	loc 96
com(110V) air valves	70	loc 96
com(110V) air valves	71	loc 96
24V sensors	72	loc 109
24V sensors	73	loc 109
24V sensors	74	loc 109
24V sensors	75	loc 109
24V sensors	76	loc 109
24V sensors	77	loc 109
24V sensors	78	loc 109
	79	
	80	

Table 6.2C - Control Box Strip Connectors

Description	Location	Description
	81	
	82	
	83	
	84	
	85	
	86	
	87	
	88	
	89	
	90	
	91	
	92	
power input (208V) L3	93	contactors 1,2,3 no3
power input (208V) L2	94	contactors 1,2,3 no2
power input (208V) L1	95	contactors 1,2,3 no1
power input (208V-COM)	96	loc 31,63
top conveyor chain motor L3	97	fuse 11
top conveyor chain motor L2	98	fuse 10
top conveyor chain motor L1	99	fuse 9
bottom conv. chain motor L3	100	fuse 14
bottom conv. chain motor L2	101	fuse 13
botom conv. chain motor L1	102	fuse 12
24V power supply (110V)	103	front door switch
PLC power supply (110V)	104	fuse 18
power input (110V) line	105	control box door switch (110V)
power input (110V-COM)	106	PLC, power supply (COM)
	107	
PLC-Y36	108	E-stop switch
power supply (24V)	109	enable switch, PLC#2,3,5,loc 72-78
power suplly (24V-COM)	110	PLC#3, contactor1-3 coil, relay1-9 coil, loc 40-46, front door led
E-stop switch	111	E-stop status(1) robot2
relay9 no2	112	E-stop status(2) robot1
E-stop status(1) robot1	113	E-stop status(2) robot2
relay9 no1	114	E-stop (9) robot2
relay9 no1	115	E-stop (10) robot2
relay8 no2	116	E-stop (10) robot1
relay9 no2	117	E-stop (9) robot1
PLC-Y34	118	relay7 no1
PLC-Y35	119	relay7 no2
PLC-X40	120	enable switch, relay7,8,9 coil, relay8 no1, relay9 no2

7 - CONTROL, MONITORING AND COMMUNICATION SOFTWARE

In order to simplify the integration of the future developments in the cell, and the implementation of the testing and demonstration software described in the next chapter, basic programs for communication among the industrial computer, programmable logic controller, and robot controllers were developed or adapted from previous research. Prior to implementing the communication programs, however, the control strategy for the cell needs to be defined. An appropriated selection of control strategy is fundamental to achieve real-time coordination, flexibility, and modularity in the Assembly Cell, and later integration with other systems in the Manufacturing, Automation and Robotic Laboratory. Network and hierarchical models are two typical control strategies.

In the Network Model, the control effort is dispersed among the elements in the cell. This strategy requires direct communication among all components involved with the control activity. The network model has an excellent response time; however, it demands a large number of interfaces and communication programs, and complicates the future inclusion of other devices in the cell.

A more popular and simpler control strategy is provided by the hierarchical model, in which the control processes are isolated by function and communicate through standard interfaces. In other words, the operations in the cell are decomposed into a sequence of tasks, which are then assigned to subordinated control modules. This model was designed to be implemented in a distributed and heterogeneous computer environment, and to permit local autonomy and integrated operation.

For the Assembly Cell the hierarchical control model was selected, with the creation of two control layers: Cell and Equipment (see Figure 7.1). This model permits real-time coordination, flexibility, and modularity in the cell, and can ease the integration into the Manufacturing, Automation and Robotic Laboratory.

The Equipment Control Level is associated with the programmable logic controller and the robot controllers, which coordinate the operations of the conveyor and the manipulators, respectively. The PLC and the robot controllers are microprocessor-based devices that can be programmed to communicate and interpret the commands sent by the workstation controller and to execute the control and monitoring of the equipment subordinate to them.

The overall operations of the assembly cell are coordinated and synchronized by the industrial computer, properly named the Cell Controller. The cell controller defines the special and temporal sequence of tasks to be performed by the robots and the conveyor.

7.1 - CELL CONTROLLER - PROGRAMMABLE LOGIC CONTROLLER COMMUNICATION

The control interfacing software between the cell controller and the TI435 programmable logic controller is done via serial communication. The Serial Interface Port of the PLC has the Communication Control Module (CCM) protocol available, which supports a structured method of exchanging information. Using this protocol, the cell controller can access the internal variable memory (v-memory) of the PLC, where the values of the timers, counters, input and output ports, stages, diagnostic information, user data, and other operands are stored. Thus, through the manipulation the data of the

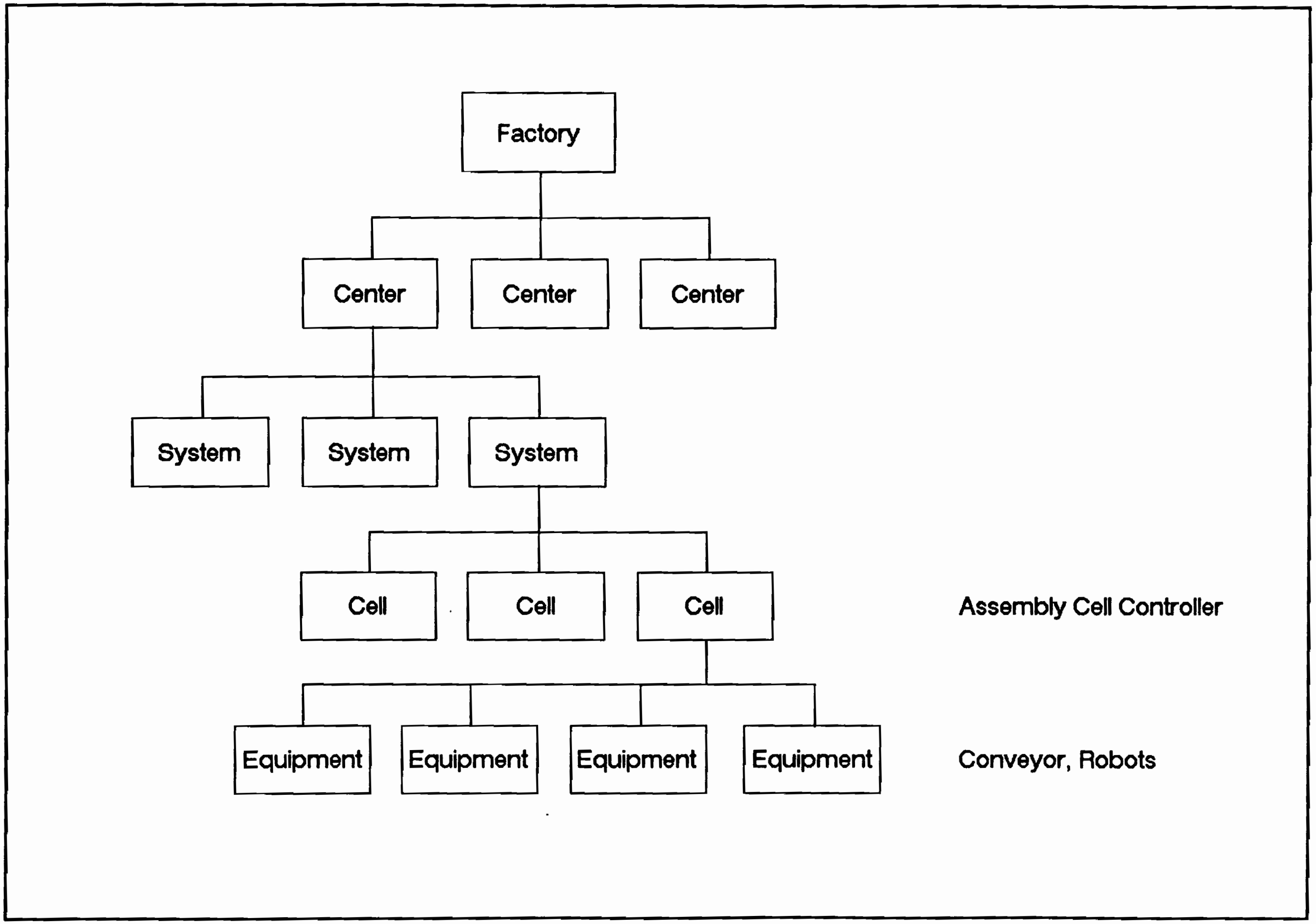


Figure 7.1 - Hierarchical Control Topology

variable memory, the cell controller can assume total control of the TI435.

Routines implementing the CCM protocol for the realtime co-processor card were developed by Ridgway [42]. These routines provide cell controller to accomplish the following operations in the PLC:

(1) Upload and download ladder programs
(2) Clear ladder memory
(3) Read and write input and output ports
(4) Read and write timers, counters, and memory values
(5) Select the PLC mode (run or program)
(6) Check the PLC mode
(7) Read error status
(8) Provide user access and denial

The programs developed by Ridgway are divided into three hierarchical levels: (1) user programs, (2) RIC supervisory functions, and (3) RIC tasks [43, 44, 45]. The RIC tasks are programs loaded into the memory of the realtime co-processor to execute the communication with the PLC, using the CCM protocol. The tasks are loaded, unloaded, and monitored by the supervisory functions, which are activated by the user's programs. The information exchange (such as RIC card number, serial port number, data to be sent, and data received) between supervisory functions and tasks is defined through parameter structures. This hierarchical model and the integration of all communication information into parameter structures, facilitates the design, development, and testing of the communication programs enormously.

7.2 - CELL CONTROLLER - ROBOTS COMMUNICATION

The exchange of data and commands between the cell controller and the robots is done through serial communication. On the robot side, the Robot Automatix Incorporated Language (RAIL) has available high-level commands to read and write numerical and textual data from/to any of the three robot controller's serial ports. For example, the command **write '/dev/portl' ('send_string')** will write the word **send_string** to serial port 1, and the statement **reads 'dev/port2' (input_string)** will read a string from serial port 2 and save as a variable named **input_string**. The RAIL also allows the user to select the format of data being sent or received via serial port, by including format specifiers with the write and read statements. No special protocol is necessary to communicate with the robots. The only requirement is to include a "carriage-return" (ASCII 13) character at the end of the information transmitted. This language, however, is flexible enough to permit the definition of additional communication parameters, programmed individually for each serial port, such as special end-of-file identifier characters, communication error codes, and retransmission of the data received (echoing).

Supervisory functions and communication tasks were implemented to read and write numerical and textual information to/from the robots by the cell controller. Since the cell controller also uses the realtime co-processor card to implement the communication with the robots, the programs developed follow the same hierarchical organization and parameter structure implemented for PLC communication.

8 - TESTING AND DEMONSTRATION SOFTWARE

The last activity for this project was the development of testing and demonstration programs to check the functionality and show the integration of the components in the cell, respectively.

The Assembly cell has fifteen devices that require integrated and coordinated operation, resulting in a large number of electronic interfaces. Testing programs are an important tool to facilitate the implementation and functional check of the equipment in the cell. The testing software implemented contains routines to monitor and control the components connected to the discrete input and output ports of the robot controllers and the programmable logic controller. In other words, the cell controller computer can directly command the lift devices, lift-and-transfer devices, elevators, check the positioning sensor in the conveyor, activate the end-effector's gripper, and supervise the communication between the PLC and the robots.

The demonstration software illustrates the concept of the hierarchical cell control strategy and shows the possibility of the integrated and synchronized operation of the components within the assembly cell. This software emulates assembly operations by controlling the motion of a set of pallets on the conveyor and supervising the motion of the manipulators. In order to accomplish the assembly simulation and allow the testing operation, programs were developed for the programmable logic controller, robot controllers, and cell controller.

The PLC program controls and monitors the motion of pallets on the conveyor during the demonstration, and stays in a waiting state during the testing, when the cell controller directly accesses its input and output ports. The exchange of command and status information between the programmable logic controller and the cell controller is accomplished through the PLC's variable memory (v-memory).

The program that runs in the robot also controls the motion of the manipulators among a pre-defined set of points when in demonstration, and reads and writes from/to its discrete input and output ports during the testing. A pre-defined set of messages is exchanged between the cell controller and the robots to command and monitor the operation of the robot.

The cell controller software executes the user interface, and coordinates and synchronizes the operations of the robots and conveyor. Through menu-driven screens, the user can control and monitor the demonstration and testing operations.

8.1 - TEST AND DEMONSTRATION EXECUTION

Before starting the execution of the test and demonstration programs, it is necessary set up the robots and the conveyor, following the procedures explained in appendix. The next step is to load and start the program of the robots by loading the file **demo** from the disk drive 0 (**load '../demo'**) and typing **demo** <enter>. After these procedures the robot controllers will initialize serial port 1 and wait for a command from the cell controller.

The programs for the cell controller are in the subdirectory **c:\assembly\celldemo**. By typing **testdemo** <enter>, the industrial computer will execute a batch program that initializes the realtime co-processor card, and start the **demo.exe** program. The demo program will initialize the serial ports, set the PLC to run mode, and show the Main Menu screen (Figure 8.1). Using the up/down arrow keys the user can select among the

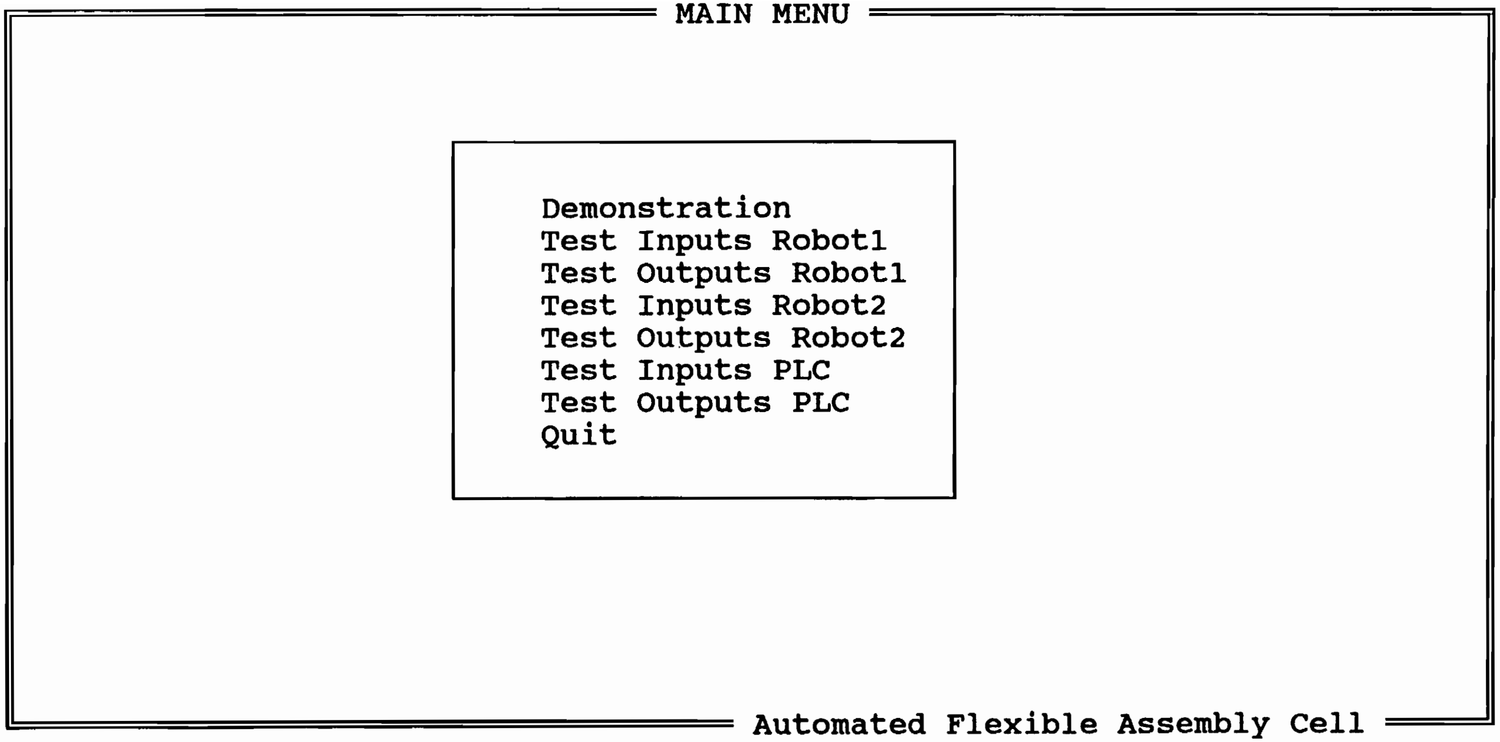
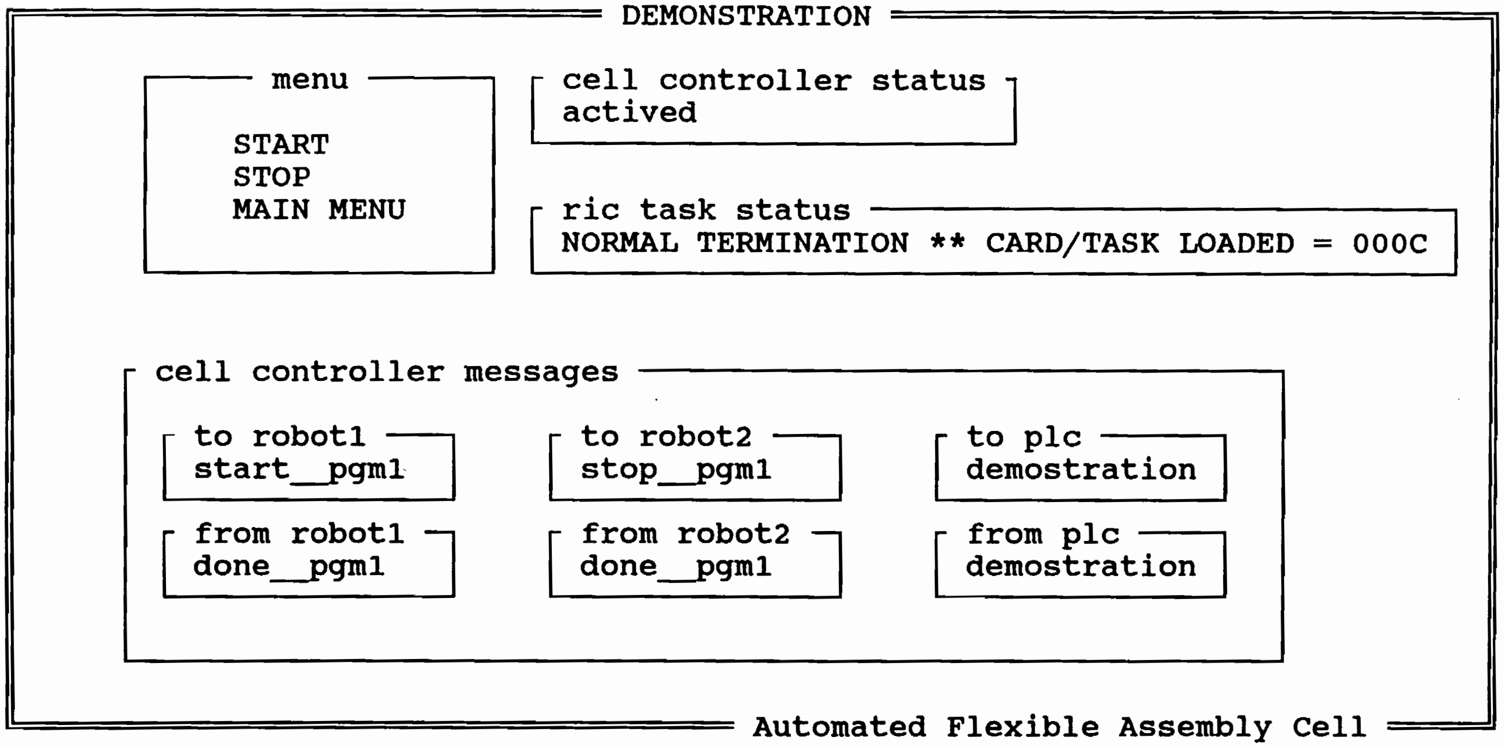


Figure 8.1 - Main Menu Screen

Demonstration, **Test Inputs Robot1**, **Test Inputs Robot1**, **Test Inputs Robot2**, **Test Inputs Robot2**, **Test Inputs PLC**, **Test Outputs PLC**, and **Quit** options.

If the demonstration option is selected, the screen shown in the Figure 8.2 is displayed. By selecting **start**, the cell controller will request the PLC to start its demonstration program (see Tables 8.1A and 8.1B). If a pallet moves to a dock position, the PLC will notify the cell controller and hold the pallet. The industrial computer will then send a message to the robot associated to that spur, requesting the start of the 'assembly operation'. With the conclusion of the 'assembly', the robot will return a status message to the cell controller, which will then authorize the PLC to release the pallet held in the dock. This cycle repeats until the user selects the **stop** option. The **stop** option causes the interruption of all operations in the cell. The demonstration can be restarted by selecting the **start** option. To quit the demonstration, first select **stop** and then **main menu**. During the execution of the demonstration the user can monitor cell control status, check the messages exchanged between the cell controller and the robots and PLCs, and, by reading the status boxes, know which task the RIC is currently executing.

The other options available on the main menu are associated with testing operations. Six tests can be executed (Figure 8.1): **read inputs robot1**, **write outputs robot1**, **read inputs robot2**, **write outputs robot2**, **read inputs PLC**, and **write outputs PLC**. The **read input robot1** and **read input robot2** menus (Figure 8.3 and Figure 8.5) show the status of the 24 discrete ports available in the robot controllers. When the port assumes level logic '1' its respective number on the computer screen turns to video reverse. The input definition box displays the devices associated with each port. To test the output ports of the robots the user needs to select the **write outputs robot1** (Figure 8.4) and **write outputs robot2** menus (Figure 8.6). These screens are similar to those used to test the input ports. The numbers in video reverse indicate the ports



```
DEMONSTRATION

menu
    START
    STOP
    MAIN MENU

cell controller status
actived

ric task status
NORMAL TERMINATION ** CARD/TASK LOADED = 000C

cell controller messages
  to robot1          to robot2          to plc
  start__pgm1        stop__pgm1         demostration

  from robot1        from robot2        from plc
  done__pgm1         done__pgm1         demostration

Automated Flexible Assembly Cell
```

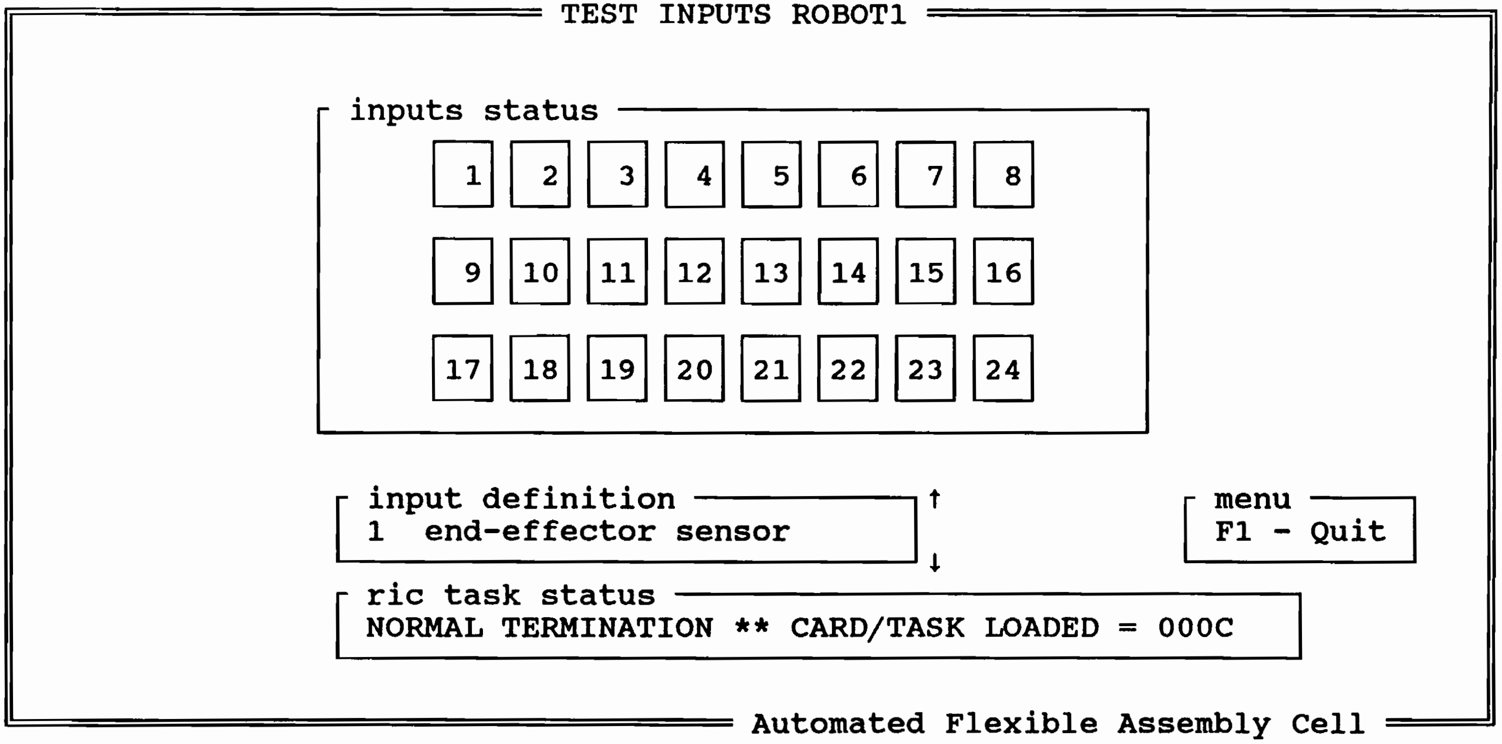
Figure 8.2 - Demonstration Software Screen

Table 8.1A - Sequence of Operations During the Demonstration

CONDITION	CELL CONTROL	PLC	ROBOT1	ROBOT2
user starts the demonstration				
	(1) writes 1 to v-mem 1400 writes **start_demo** to robots			
		(2) initializes conveyor and writes 1 to v-mem 1403	(2) starts demo loop	(2) starts demo loop
pallet arrives at dock 1				
		(1) writes 1 to v-mem 1404 and holds pallet		
	(2) sends **start__pgm1** to robot 1			
			(3) starts assembly	
robot 1 finishes assembly				
			(1) sends **done__pgm1**	
	(2) writes 0 to v-mem 1404			
		(3) returns pallet to main conveyor		

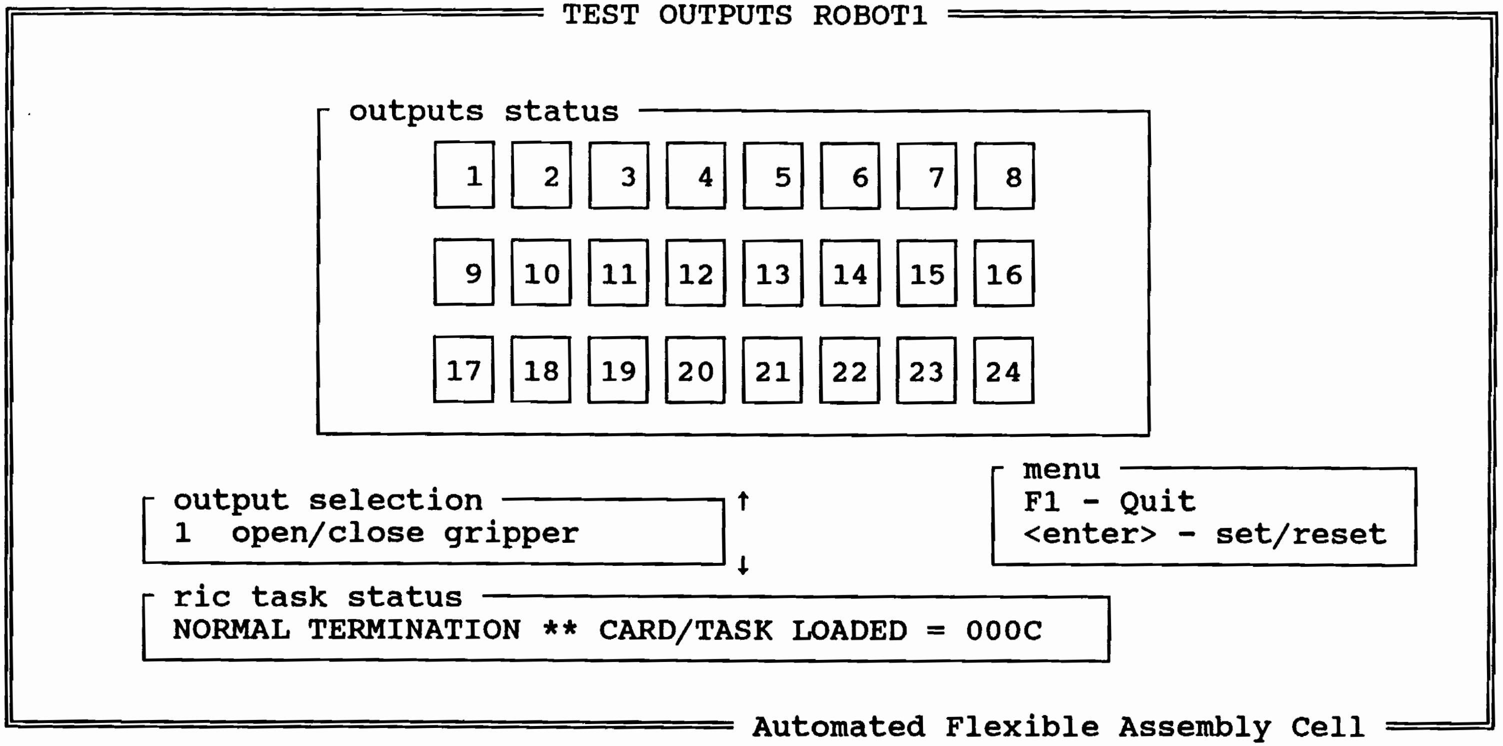
Table 8.1B - Sequence of Operations During the Demonstration

CONDITION	CELL CONTROL	PLC	ROBOT1	ROBOT2
pallet arrives at dock 2				
		(1) writes 1 to v-mem 1405 and holds pallet		
	(2) sends **start__pgm1** to robot 2			
				(3) starts assembly
robot 2 finishes assembly				(1) sends **done__pgm1**
	(2) writes 0 to v-mem 1405			
		(3) returns pallet to main conveyor		
user stops the demonstration				
	(1) write 0 to v-mem 1400 write **quit__demo** to robots	(2) stops conveyor writes 0 to v-mem 1403	(3) quits demo loop	(3) quits demo loop



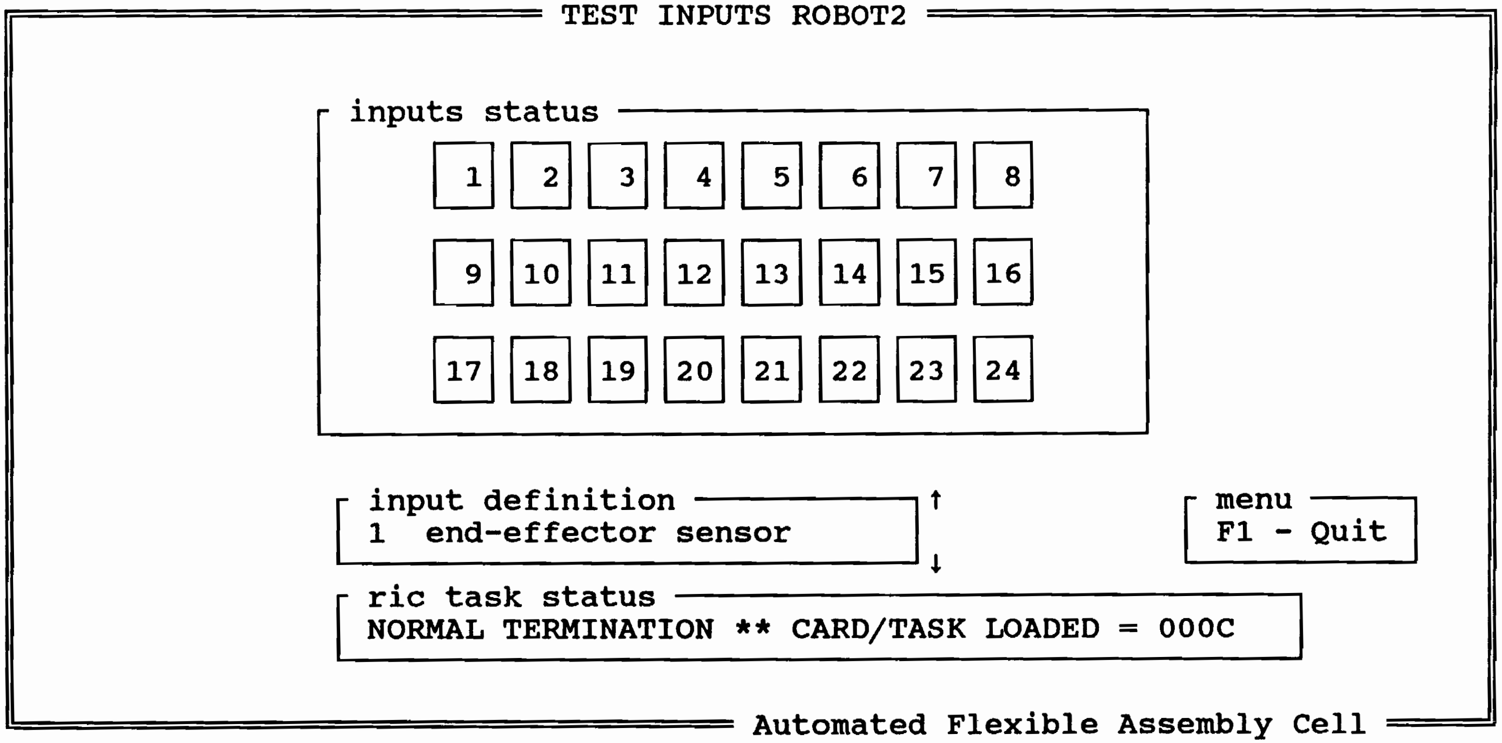
```
TEST INPUTS ROBOT1

inputs status
   1   2   3   4   5   6   7   8

   9  10  11  12  13  14  15  16

  17  18  19  20  21  22  23  24

input definition                              menu
1  end-effector sensor                        F1 - Quit

ric task status
NORMAL TERMINATION ** CARD/TASK LOADED = 000C

                                  Automated Flexible Assembly Cell
```

Figure 8.3 - Test Inputs Robot1 Screen



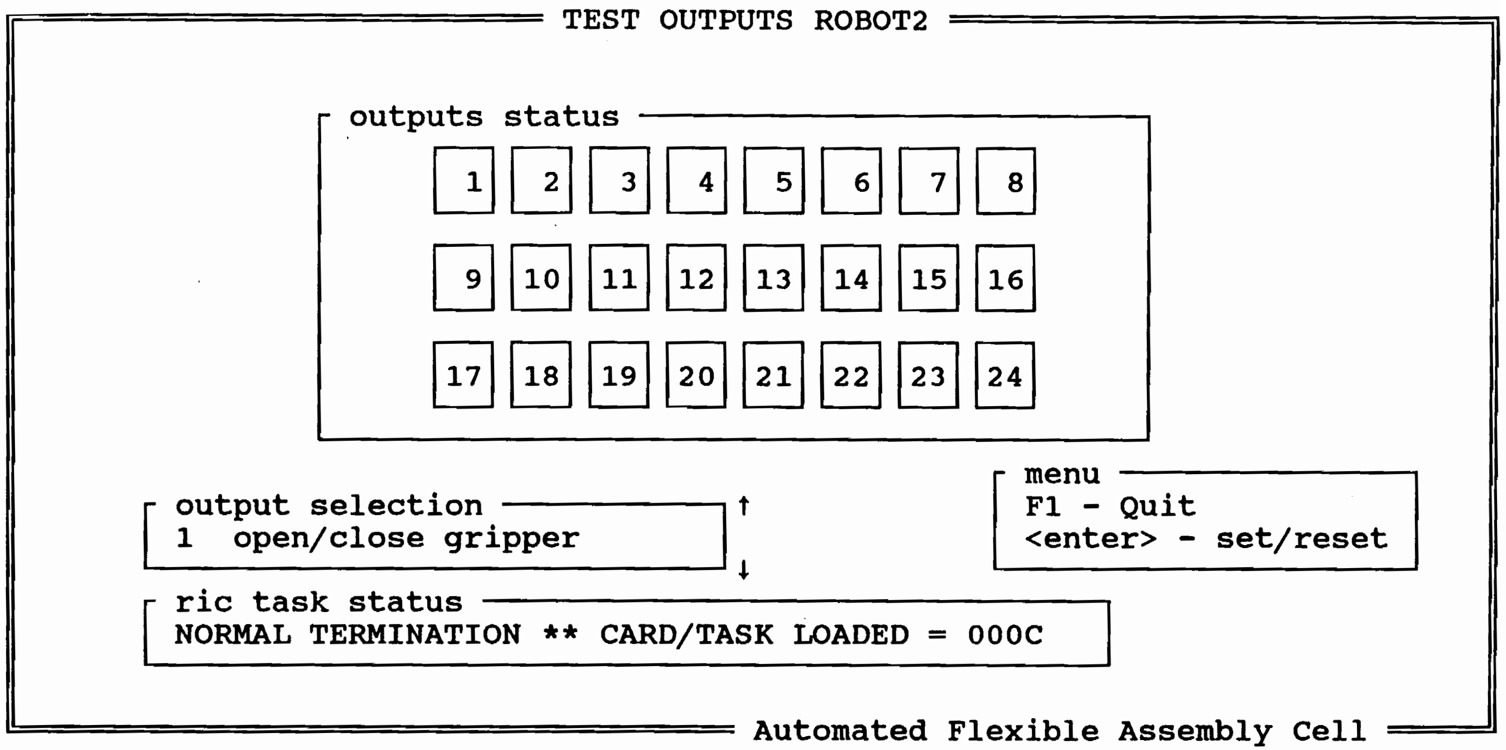
```
TEST OUTPUTS ROBOT1

outputs status
   1   2   3   4   5   6   7   8
   9  10  11  12  13  14  15  16
  17  18  19  20  21  22  23  24

output selection                 ↑      menu
1  open/close gripper                   F1 - Quit
                                 ↓      <enter> - set/reset
ric task status
NORMAL TERMINATION ** CARD/TASK LOADED = 000C

Automated Flexible Assembly Cell
```

Figure 8.4 - Test Outputs Robot1 Screen



```
TEST INPUTS ROBOT2

inputs status
  1   2   3   4   5   6   7   8
  9  10  11  12  13  14  15  16
 17  18  19  20  21  22  23  24

input definition                          menu
1  end-effector sensor                    F1 - Quit

ric task status
NORMAL TERMINATION ** CARD/TASK LOADED = 000C

                        Automated Flexible Assembly Cell
```

Figure 8.5 - Test Inputs Robot2 Screen

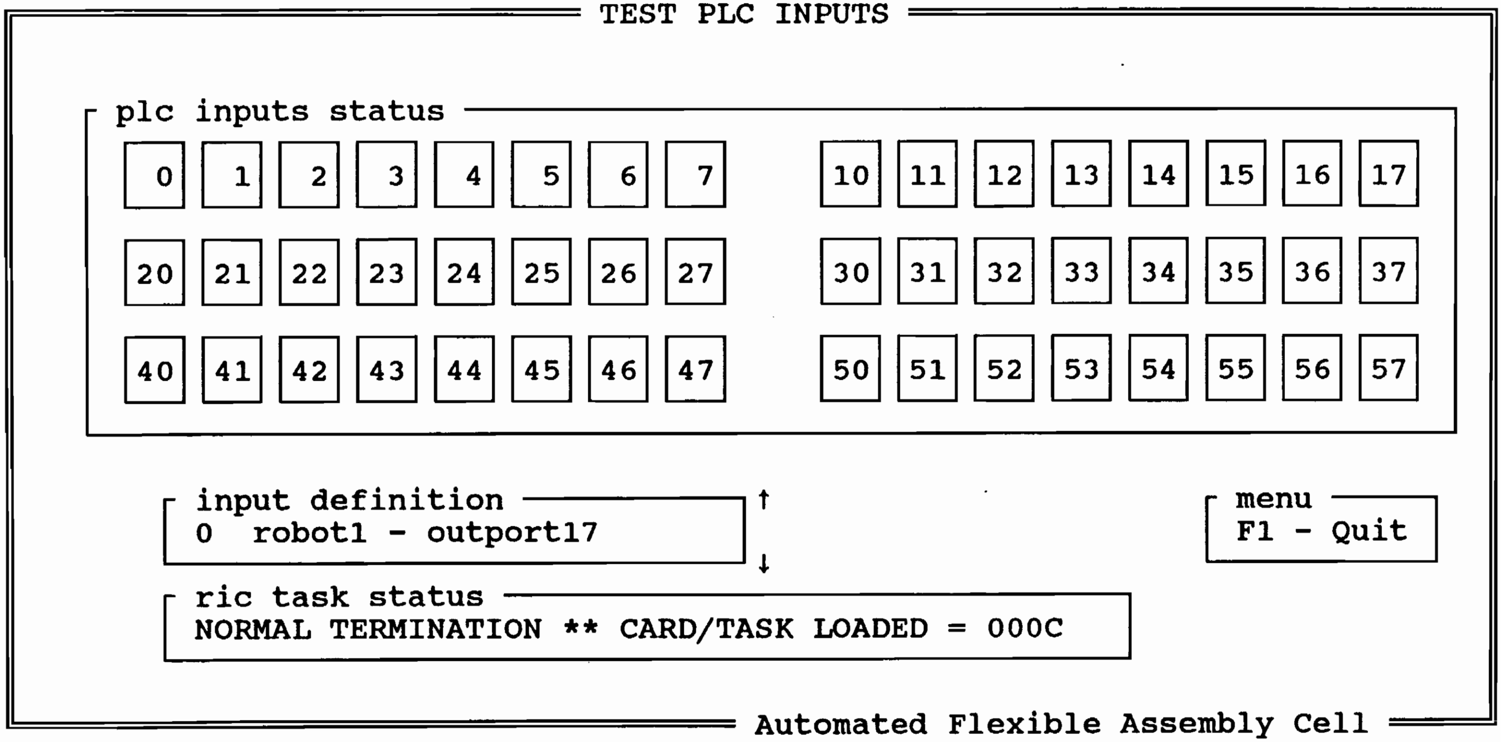


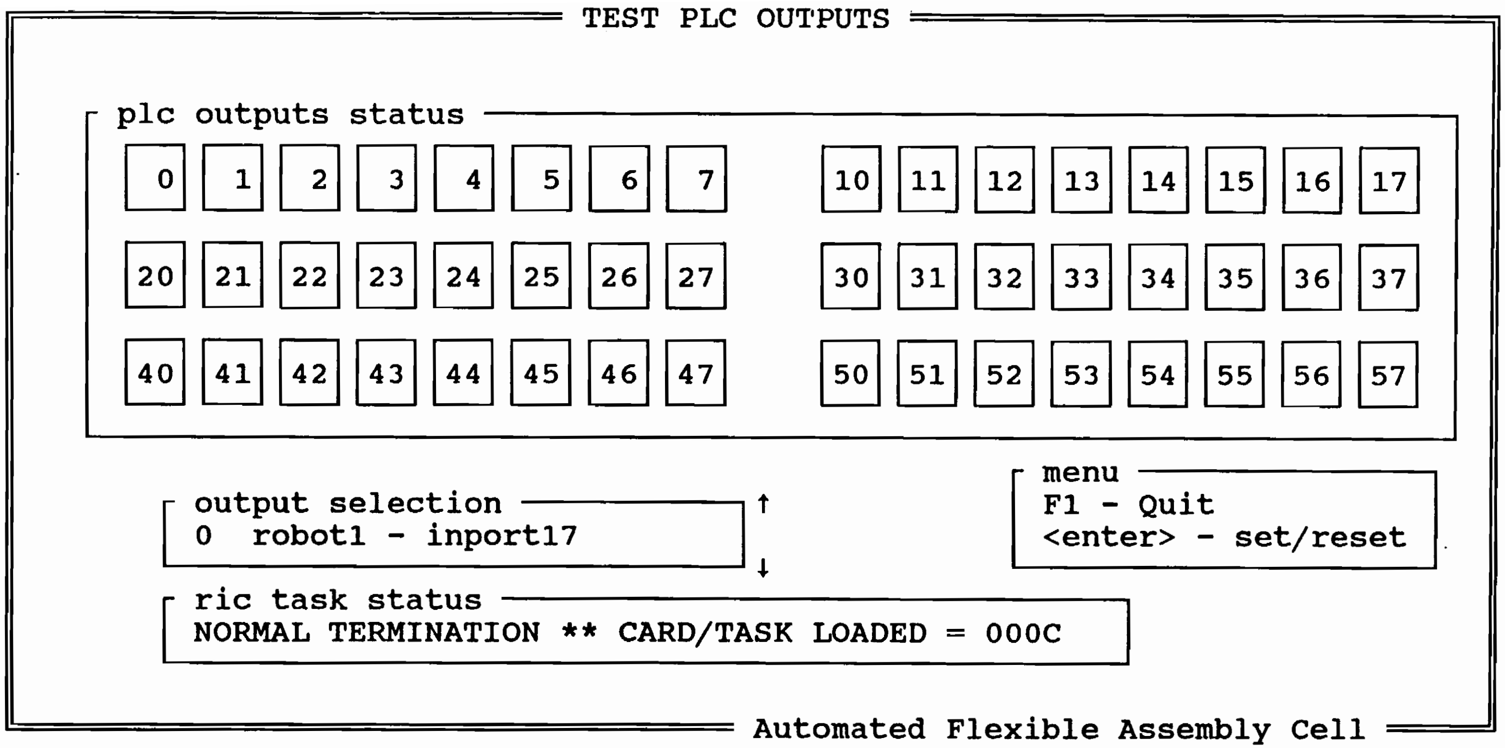
```
TEST OUTPUTS ROBOT2

outputs status
  1   2   3   4   5   6   7   8
  9  10  11  12  13  14  15  16
 17  18  19  20  21  22  23  24

output selection                       menu
1  open/close gripper                  F1 - Quit
                                       <enter> - set/reset
ric task status
NORMAL TERMINATION ** CARD/TASK LOADED = 000C

Automated Flexible Assembly Cell
```

Figure 8.6 - Test Outputs Robot2 Screen

activated. To change the condition of an output, the user selects the desired port on the selection box and presses the key **enter**.

The screens to read from the input (Figure 8.7) and write to the output (Figure 8.8) ports of the PLC have the same layout and operation procedures described for the robots. The only change is the larger number of ports monitored and controlled by the cell controller.





```
TEST PLC OUTPUTS

plc outputs status
 0   1   2   3   4   5   6   7      10  11  12  13  14  15  16  17
20  21  22  23  24  25  26  27      30  31  32  33  34  35  36  37
40  41  42  43  44  45  46  47      50  51  52  53  54  55  56  57

output selection                            menu
0  robot1 - inport17                        F1 - Quit
                                            <enter> - set/reset
ric task status
NORMAL TERMINATION ** CARD/TASK LOADED = 000C

Automated Flexible Assembly Cell
```

Figure 8.8 - Test Outputs PLC Screen

9 - CONCLUSIONS AND RECOMMENDATIONS

The objective for this project was to create an automated flexible assembly cell to be the test bed for basic and applied research in the areas of (1) system configuration, (2) sensing, (3) end effector and manipulator, (4) part storage, feeding and presentation; and (5) parts mating.

Mechanical integration, electrical interconnecting, and communication software among the cell components were designed and implemented in order to active final configuration. As a result, a working assembly cell is available with basic control, monitoring, testing, and demonstration software. The success of this project is also observed with the fulfillment of most of the requirements imposed on the cell. These requirements were: (1) the MARL physical location and integration with other systems' constraints, (2) free physical space inside and outside the robots' work envelopes, (3) access to electrical power and standard and modular electrical interfaces for future integration devices associated with the research areas; and (4) allocation of space for installation, operation, and maintenance of the assembly cell.

Future works in the assembly cell can be associated with the specific research activities or general improvements. Some opportunities for general improvements are related to (1) implementation of safety measures, including the physical and electronic barriers, alert signals, and lights, (2) development of communication protocols between the robots and the cell controller, including error recovery procedures, (3) inclusion of mechanical devices to assist in orientation of the pallets on the conveyor, and (4) integration of the assembly cell with other systems in the Manufacturing, Automation and Robotic Laboratory.

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APPENDIX - ASSEMBLY CELL OPERATION

Before executing any operation in the assembly cell, read carefully the user's manuals and other information associated with devices present in the cell, and the chapters 4 through 7 of this project report. Be aware of the safety procedures and operational recommendations described in those documents. After that, to operate the entire assembly cell execute the steps described below. If all devices are properly operating the cell will be ready to run any application.

1. Turn on the switch breakers 1,2,3 and 32
2. Turn on the switch on the front door of the control box
3. Turn on the air valve
4. Turn on the robot controllers 1 and 2
5. Release all emergency switches
6. Active PLC output Y36
7. Enable the cell by pressing and releasing the **enable** button attached to the cell

   controller rack
8. Enable the robot motors calibrate the robots by pressing the button **motor on**
9. Calibrate the robots by pressing the **calibrate** button

To use only the PLC and the conveyor execute the steps 1, 2, 3, and 7 previously described, and keep hold the **enable** button. In order to work with the robots it is necessary to accomplish the steps 3, 4 5, 8, and 9; then hold the enable button. The user must notice that by holding the **enable** button the assembly cell emergency stop circuit is bypassed. This procedure **does not** disable the internal emergency stop circuit of any of the cell devices. For safety reasons, **the enable button must be released during the operation of the assembly cell.**

If an emergency stop condition occurs during the operation of the cell all the devices will be disabled; except the PLC and the 24V power supply. An emergency stop condition will take place when the robots override theirs operation limits, the PLC disables output port Y36, or the user presses any of the emergency buttons available in the assembly cell. To restart the operation of the assembly cell after an emergency stop, first eliminate the cause of the disruption and then press and release the enable button.

CAUTION

The Assembly Cell contains HIGH VOLTAGE devices and ONLY authorized people can check, modify, or replace of any wire or component within the cell.

VITA

Nei Edison Mueller was born on February 21, 1961 in Brazil. He received a Bachelor's degree in Electrical Engineering from the Universidade Federal de Santa Catarina, Brazil, in 1983. He worked for a research institute in Brazil from 1983 to 1990, where he participated in several automation projects as a design engineer, project leader, and department manager. He then enrolled in the Department of Industrial and Systems Engineering at Virginia Polytechnic Institute and State University for a Master of Engineering degree.

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