Automated Storage and Retrieval System Design Report

by

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Automated Storage and Retrieval System (AS/RS) Design Report

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(ABSTRACT)

This report describes the design and operation of an Automated Storage and Retrieval System (AS/RS) to serve the Flexible Manufacturing and Assembly System (FMAS) in the Manufacturing Systems Laboratory at Virginia Tech. The system requirements of the AS/RS, justification of design choices, and the proposed modes of operating the system are described.

The AS/RS was designed to automatically move material on pallets between the storage racks in the laboratory to the FMAS conveyor interface. The system was designed and built, and has been tested to perform the desired operating functions. The scope of this project was limited to designing and installing the hardware component of the AS/RS, and testing it to ensure that it will satisfy the system requirements of the FMAS. The educational objective of the project is to enable fully automated control of all cell activities via the FMAS Computer Network.

Acknowledgments

I would like to make known my appreciation to all those who have helped me to design and build this machine.

Dr. Deisenroth, for his expert guidance and advice throughout the project.

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Table of Contents

List of Figures

1. INTRODUCTION

1.1 Background

The Robotics and Automation Laboratory at Virginia Tech provides facilities for research and teaching in advanced production methods and automation. It is an ongoing area of development, and new systems continue to be designed and installed, reflecting the rapid changes in technology in this field. A Flexible Manufacturing and Assembly System (FMAS) has been developed to demonstrate the use of industrial robots and CNC milling machines in an industrial manufacturing environment. The system is used primarily for instruction and research in robotics, industrial automation and system integration. In order to more completely emulate a typical production process, an Automated Storage and Retrieval System (AS/RS) was developed as a result of this project. The AS/RS will provide storage for raw materials, components, and completed products. Materials and components can be drawn from the storage system when required, and fully assembled products can exit the manufacturing system into an inventory holding area, designated in the storage rack.

The need for this addition to the FMAS was driven by developments in industry. The drive to create flexible manufacturing systems has resulted in a need for small unit load AS/RS in manufacturing environments. They are mostly used to provide storage of materials and components close to the workcell, but may also be used as buffer storage for semi-completed assemblies, or for completed products exiting the workcell. By providing this facility in the laboratory, one will be able to demonstrate the typical operation of flexible manufacturing systems as they are used in industry. System integration is also shown to be of great importance, and students and researchers will gain an appreciation of the complexities involved in integrating the control functions of these systems.

1.2 Description of the FMAS

The FMAS consists of two IBM robots, two DYNA CNC milling machines, an assembly table, a Shuttleworth Slip Torque conveyor system, and a network of personal computers and a TI 565 PLC which control the workcell functions and the material handling system. A schematic representation of the FMAS is shown in Figure 1.1. The system also utilizes the following software to control the system: Microsoft MS-DOS 5.0 and Windows 3.1 operating systems, a Borland C++ compiler, IBM AML/E robot programming language, Texas Instruments TISOFT relay ladder logic software, CADKEY, and Cutting Edge [1]. In order to illustrate the functioning of the system, a typical production process is described.

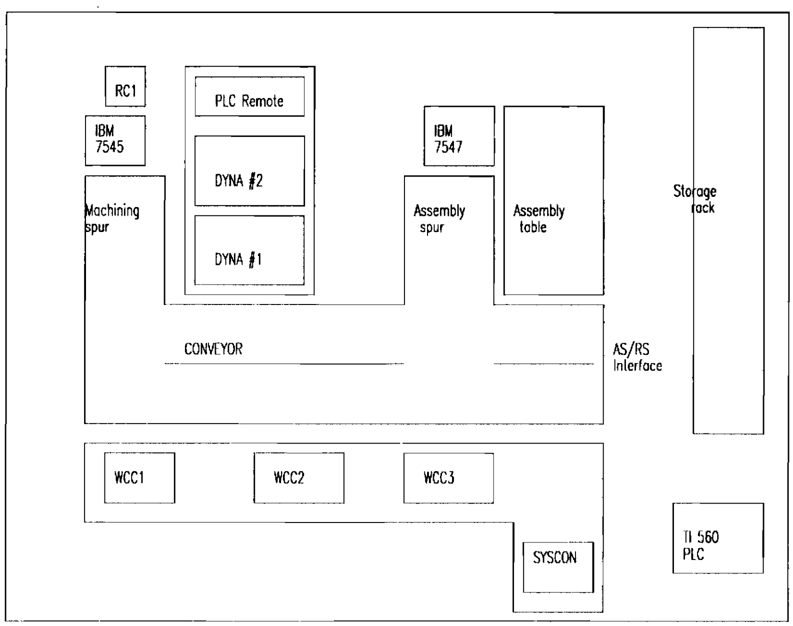

Figure 1.1: Schematic of the Virginia Tech FMAS [1].

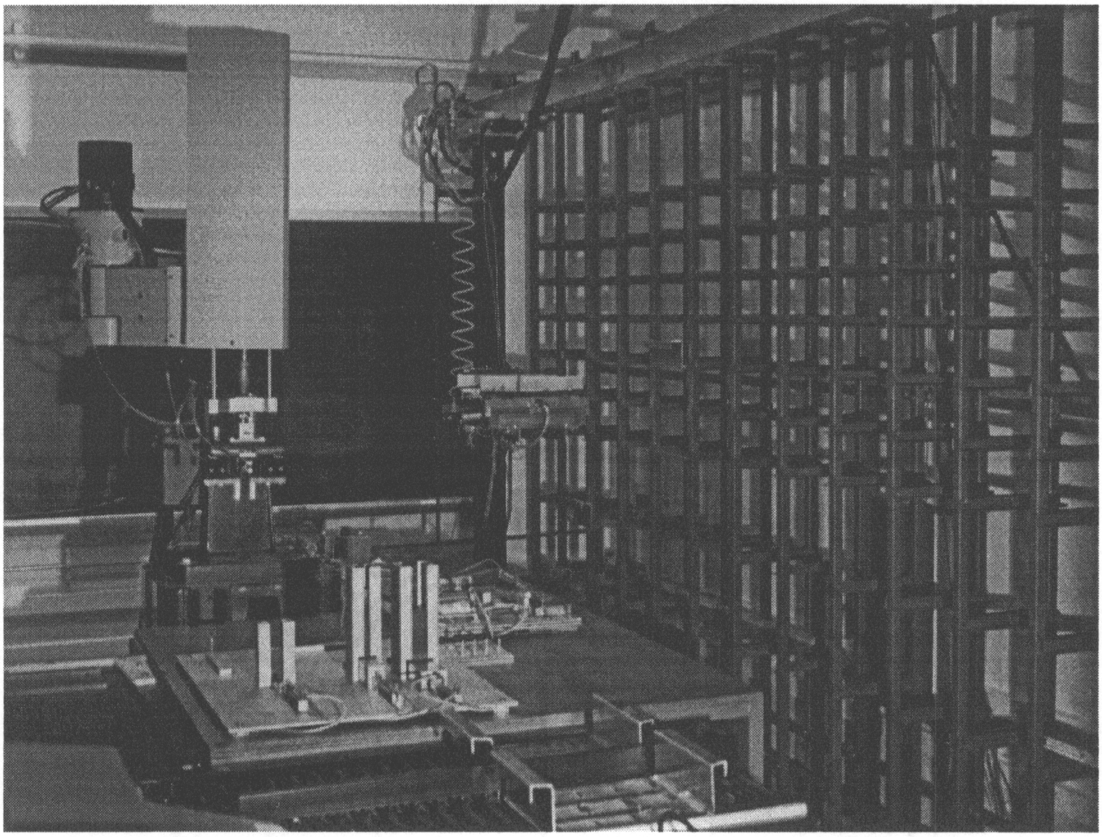

Figure 1.2: View of AS/RS with robot, assembly table, and conveyor.

1.2.1 Example of production using the FMAS (refer to Figure 1.1)

Raw material enters the system at the AS/RS interface on pallets. The movement of pallets is controlled by the personal computer labeled WCC3, in conjunction with the TI 565 PLC. The pallet motion is monitored using optical sensors mounted in the conveyor track. Typically, material will travel to the machining workcell, which is controlled by the personal computer WCC1, as well as the IBM 7545 robot controller. When the pallet arrives at the end of the machining spur, it is locked in position and the IBM 7545 robot unloads the raw material into fixtures on one of the DYNA CNC milling machines in the workcell. Machining operations then take place, and when completed, the robot unloads the finished components and places them in positions on a pallet. The pallet is then transferred via the conveyor to the assembly spur. The IBM 7547 robot unloads the components from the pallet and places them into fixtures on the assembly table. The robot is then used to assemble the product, and loads them into a pallet for dispatching to finished goods inventory, via the conveyor system. The operations at this workcell are controlled by the personal computer labeled WCC2.

1.3 Project Objective and Scope

Integration of manufacturing systems is a major challenge to the industry and is a topic which receives much attention in teaching and research in this field. The scope of this project was limited to designing and installing the hardware component of the AS/RS, and testing it to ensure that it will satisfy the system requirements of the FMAS. The design of the control software, and integration into the FMAS will be carried out in a subsequent project.

Physical integration of the AS/RS into the existing system was an important goal of this project. In order to integrate the AS/RS into the FMAS, it was necessary to define all possible interactions required between the AS/RS and the control system. The existing infrastructure imposes physical constraints which are a major concern during the system design process. The physical integration of new systems hardware with existing systems presents problems for the system designers which are difficult to comprehend without first hand knowledge of the implementation process. The system design process in this case, draws on a thorough understanding of advanced manufacturing systems, especially the functioning of Flexible Manufacturing Systems (FMS) and the material handling systems which serve these FMS workcells. The system design process also requires knowledge and understanding of the various design approaches available, and considerations of system reliability and maintainability. In the continuously evolving laboratory environment, it is important to build sufficient flexibility into the design to allow modifications or expansion of the system if they are required.

Although the control software is beyond the scope of this project, consideration of the interactions between the AS/RS and the controlling hardware and software was of primary importance to the design. Logical inputs and outputs were tailored for direct control using a Texas Instruments TI 565 PLC to control the functioning of the AS/RS. This has the advantage of allowing flexibility of programming of the storage and retrieval functions of the system, and also fitting into the existing control hierarchy of the FMAS. This will also enable fully automated control of all cell activities via the FMAS Computer Network.

2. LITERATURE REVIEW: DESIGN AND OPERATION OF A UNIT LOAD AS/RS

2.1 Description of an Unit Load AS/RS

The Materials Handling Institute defines an Automated Storage and Retrieval System (AS/RS) as "A combination of equipment and controls which handles, stores, and retrieves materials with precision, accuracy, and speed under a defined degree of automation [11]." For the purposes of this project, a unit load AS/RS is more specifically a system which transports loads on pallets or specifically designed bins. These systems are usually computer controlled and the handling of pallets is fully automated. The major component parts of an AS/RS are described here, with specific reference to the requirements of the Virginia Tech FMAS [9].

2.1.1 Storage structure

This consists of a fabricated steel framework, which supports the stored loads. Important design considerations are the size of racks and compartments, design loads to be carried, and the rigidity of structures. In the case of this system, the rack had already been installed on the north wall of the laboratory, and the storage and retrieval machine was designed to service the existing infrastructure.

2.1.2 S/R machine (or Crane)

The S/R machine is used to carry out movements of material. It is capable of vertical and horizontal travel to align the load carriage with the storage compartments, or with the point of loading/delivery. It must be capable of fetching or delivering the load to/from the storage compartments, and at points of loading/delivery to the system. Important design considerations are the travel speeds, load transfer/pickup mechanisms, and intelligent control of the machine to locate storage compartments. This project was largely concerned with the design and construction of the crane itself, rather than the control system, which will be designed and implemented at a later stage.

2.1.3 Storage modules

These are the pallets, bins, baskets or any other containers used to carry the unit load. They must be capable of being transferred to and from the storage racks, and each of the interfaces to the AS/RS. This system uses the existing pallets, which were designed to accommodate parts used in the FMAS. The pallets are described more completely in Section 3.2.2 of this report.

2.1.4 Pickup-and-deposit stations

These are the transfer stations for material entering or leaving the AS/RS; the interface with the material handling systems external to the AS/RS. There is only one pick-up and deposit station in the Virginia Tech AS/RS, positioned at the end of the Shuttleworth Conveyor system, closest to the storage rack. In order to allow a station at which a pallet can stand at rest, a short section of additional conveyor is necessary between the end of the conveyor system and the crane pick-up point. This is defined as the conveyor interface, and is more completely specified Section 3.2.3.

2.1.5 Control equipment

The control equipment must perform a wide variety of functions which include the selection of items, load identification, order picking, control of devices, inventory control, and interaction with users. Typically this is achieved using a central computer controlling remote programmable controllers, and user interfaces such as CRT screens, keyboards, and printers. Sensors to position devices and loads in the system, as well as load identification using bar-code readers are used for controlling the system, as well as feeding inputs to the information system. Reliability of the control system is an important design consideration, which can be increased by using better quality sensors and limit switches; building in redundant circuitry; better quality control in the manufacture of system components; and design for maintainability [6], [2]. The design of the control system is beyond the scope of this project, although many of the monitoring devices such as sensors and limit switches form part of the AS/RS.

2.2 General Design Guidelines

In designing the system, the following general guidelines were considered important for the development of this AS/RS design.

2.2.1 Basics of material handling

The principles of good material handling practice have been well documented. Several sources list the Material Handling Institute's "Principles of Material Handling [12]." There is extensive commentary on the application of these principles in several of the references, and it would be advisable to use the Material Handling Institute's list as a checklist when designing any material handling system. In the university environment, where new methods are likely to be developed and applied to these systems, it is very important to build in sufficient flexibility in the system, so that changes reflecting the innovations can easily be accommodated.

2.2.2 Integration of systems

Integration of the AS/RS into the existing flexible manufacturing and assembly system was one of the prime objectives of this design. The existence of the conveyor and pallets imposed major constraints on the design of the system.

2.2.3 Performance criteria

Design criteria suggested for an AS/RS by Groover[9] are; storage capacity, system throughput, utilization rate, and reliability. To this list one could add measures of installation costs, operating costs and maintenance costs, as these are usually of crucial importance.

2.2.4 Reliability of the system

The importance of reliability of the system cannot be over-emphasized. The AS/RS usually serves manufacturing and or distribution centers which cannot function properly if starved of material, and thus it is vitally important to prevent breakdowns in the material handling system. Sims [18] describes some of the qualitative criteria which are useful for comparative analysis of the reliability of systems, and it is also important to consider quantitative measures of reliability which may be stated as system requirements. Dieter [5], and Blanchard [2], provide several examples of how the reliability of components and systems can be quantified, and compared.

Increased reliability can be designed into the system by focusing attention on:

- increasing the redundancy of components;
- increasing the durability or robustness of design, by increasing safety margins;
- increasing damage tolerance in the design and selection of materials;
- ensuring simplicity of design;
- building in ease of inspection and maintainability of the system.

2.2.5 Existing Technology

Automated storage and retrieval systems are in general use in industry and logistics organizations. As there seemed to be little benefit in 're-inventing the wheel,' this design was modeled on system designs which are already in use. The relatively small size of the system allowed significantly different solutions from those most commonly used in industry. The severe limitation of funds available for the project provided the incentive for using second-hand components from Virginia Tech surplus equipment.

2.2.6 Simplicity

One of the fundamental precepts of material handling in manufacturing systems is that it adds no value to the product being handled. To ensure the least cost of material handling a principal objective of this design was to minimize the amount of capital invested in the material handling system. Simplification of the design reduces the complexity of manufacture, as well as allowing possible increases in robustness and reliability. In general, the cost to make the system, as well as cost of running the system will be reduced by design simplification. It has been observed from life cycle cost studies [1], that up to eighty percent of the costs of operation are committed during the design phase of a system. Economic factors were of prime importance during the initial design process.

2.2.7 Robustness

The system will be subjected to testing and research by people who may have little or no prior experience using these systems. This system should be able to withstand any erroneous commands or operating methods. Machinery has been designed to be robust enough to withstand abusive operating conditions and greater stresses than expected from its planned use. Functional controls and logic are designed to be simple to understand and operate, allowing greater ease of programming for the control system.

2.3 Specific Design Guidelines and Operating Characteristics of Automated Storage and Retrieval Systems

In order to define the functioning of the AS/RS, it is necessary to first define some of the terminology used.

2.3.1 Operational parameters

The operational parameters used to describe the performance of the AS/RS are described by Bozer and White [4], and Han, et al [10], using the following definitions and terminology:

Travel speeds:

s_h = horizontal travel speed   Rack length L=14 feet

s_v = vertical travel speed   Rack height H=7.5 ft.

Travel time:

t_h = time to travel horizontally from I/O point to furthest column = L/s_h

t_v = time to travel vertically from I/O point to furthest level = H/s_v

Parameters: $T = \max(t_h, t_v)$ $Q = \min(t_h/t_v, t_v/t_h)$

Shape factor: $b = \min(t_h/T, t_v/T)$ $0 <= b <= 1$

Square in time: note that if rack dimensions and travel speeds are such that $t_h = t_v$, then b = 1, and rack is said to be square in time.

Transaction times: these are the times required to store and/or retrieve a unit load.

Single Command Transaction (SC): a single storage or retrieval is performed; storage cycle time includes time to load at I/O station, move time to storage location, time to deposit load, and time to return to I/O point.

Dual Command Transaction (DC): a storage and a retrieval is performed; cycle time includes time to load at I/O point time to travel to storage location, time to deposit load, time to travel to retrieve location, time to load retrieval load, and time to return to I/O point.

Formulations for transaction cycle times are:

$$T_{sc} = T\ (1 + (Q^2)/3) + 2\ T_p/d$$

$$T_{dc} = T/30\ (40 + 15\ Q^2 - Q^3) + 4\ T_p/d$$

Pickup/Delivery Time (Tp/d): time to transfer load from S/R machine to rack or vice versa.

Dwell point: this is the location of the S/R machine when it becomes idle. The Virginia Tech AS/RS designated dwell point will be the midpoint of the rack, although this has had little or no effect on the mechanical design of the crane.

Machine utilization:

The workload required of the machine is calculated as the amount of time per hour it would be busy fulfilling the throughput requirement. This is then expressed as a percentage of the hour to give the utilization figure. The accepted norm in industry for such systems is approximately eighty five percent.

Workload = no. of SC stores x T_{sc} + no. of SC retrieves x T_{sc}
+ no. of DC str/retrieves x T_{dc}

Utilization = workload x 100 / 60 = utilization %

Throughput Capacity:

This is the maximum number of loads into and out of the system expressed as a rate. Some measure of the fluctuations of demand cycles should also be determined, as most systems are not designed to operate at maximum capacity all of the time. Thirty two cycles per hour for SC and twenty two cycles per hour for DC are suggested as initial design parameters for these cranes by P&H, a major crane manufacturer.

The Virginia Tech AS/RS was proposed to achieve the same or better performance, to realistically represent an industrial environment. These measures of performance are evaluated during testing of the completed system, and compared with the typical values of similar systems in industry.

2.3.2 Physical system dimensions

Dimensions and weight of the load to be stored. In cases where a number of items are handled as one package, the size of the total load to be carried must be determined. Orientation of load must be considered as the width or depth of storage racks will be affected. Weight affects the design of the rack structure. In this case the unit load size was predetermined by the original pallet design, and the intended use of the system for small component assemblies.

Number of units to be stored. Total storage capacity requirement must be determined from system users, both present and forecast future demand should be determined. This was decided at an earlier stage, with the available space constraint being the determining factor in designing the size of the storage rack.

2.3.3 Optimization

Numerous models have been presented for the optimization of AS/RS operations. These include methods of optimizing storage facilities, considering travel time from input/output points, rack orientation and dimensions, stacking patterns, class-based storage, order picking. Bozer and White[4] provide expressions for SC and DC travel time using randomized storage and for I/O locations other than at corners of the rack. Schwartz, Graves and Hausman [17], review some of the methods used to model class based storage systems, as well as the application of techniques to decide on class boundaries, and rules applicable to the models which they have proposed. Rosenblatt [15], demonstrated that by grouping items in relatively few classes of usage, considerable improvements in the performance of the system could be achieved. Eynan and Rosenblatt [8] extended that research with models for travel times in class based systems in rectangular storage racks. Han, et. al, [10] present a method for choosing the sequence in which retrievals are sequenced in order to minimize travel time, and thus increase throughput of the system.

These methods of optimization are largely concerned with the control system of the AS/RS, and thus fall outside the scope of this project. It was useful, however to consider the strategies to be used when defining what motions may be required of the crane itself, and to allow sufficient flexibility in how the motions of the crane are controlled, to satisfy any future demands of the system.

2.3.4 Design and Safety Standards

The mechanical and structural design of the AS/RS generally follow accepted engineering guidelines, however there are several standards to which the design must conform. The American Society of Mechanical Engineers (ASME) has a published standard ASME B30.13-1991 (revision of ANSI/ASME B.30-1985), which applies to the construction, operation, inspection, and maintenance of automated storage and retrieval machines. It also cites references to the following relevant codes and standards:

- ANSI (American National Standards Institute) MH16.1-1974, Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks
- ANSI/NFPA (National Fire Protection Association) 70-1987, National Electrical Code
- ANSI/NFPA 231C-1986, Rack Storage of Materials
- Manual of Steel Construction (American Institute of Steel Construction)
- ANSI/AWS (American Welding Society) D1.1-86, Structural Welding Code-Steel.

For the purpose of this project, and given the flexibility allowed in the laboratory environment, the majority of these codes could not be strictly applied to this design. Compliance with most of the requirements is relatively simple however, due to the limited size of the application, and the relatively light loads being carried by the system. Electrical code requirements and general safety requirements of the university laboratory were strictly followed.

2.4 Design Approach

In choosing which design approach to apply in this AS/RS design, the following approaches were considered.

2.4.1 Economic design models

There are a number of economic models available to design material handling systems. Noble and Tanchoco [13], reviewed a number of the approaches which have been taken to model the design of material handling systems. The common approach is to structure models of the various types of material handling systems, using desired performance parameters, available resources of space and funds, and then to compare the relative merits of each system. The models created are usually empirically determined from existing systems, with certain key inputs which, to a large extent, determine the design of the system, by factoring in size, cost and performance. The advantage of this approach is that a system can be quickly modeled using existing material handling solutions, and estimated costs, sizes and performance parameters can be quickly evaluated for the alternatives. The method is better suited for application by equipment vendors, for tenders on frequently used designs, utilizing their own decision knowledge base.

2.4.2 Engineering design approach

The engineering approach to designing a material handling system typically follows conventional product design practice. One such approach is illustrated by Dieter [5], and can be adapted for use in the design process for the installation of an AS/RS in a flexible manufacturing environment. The success of the engineering approach depends largely on the analysis carried out in formulating the problem. Problem definition includes: assessment of the engineering objectives; correctly applying the constraints on possible solutions; and defining the criteria by which the design will be evaluated. Application of creative techniques to generate alternative solutions gives designers the freedom to look for new solutions to problems which have been solved previously. While it is important to use existing knowledge to make design decisions, the process should not be constrained to only reproducing modified versions of old designs.

2.4.3 Concurrent approach to design

The concurrent approach to the design process is of value to any materials handling system, and especially to the AS/RS. White [19], explains integration as incorporating the "...interfacing and coordination of functions, the linkages of physical components, and the information hand-offs that occur,...throughout the organization." As mentioned previously, the design of an AS/RS will often include the information system which handles inventory or other handling transactions. While the integration of the AS/RS into the existing FMAS is important, there was little teamwork required in this particular design process, and the additional complexity of the concurrent approach was therefore not justifiable for this design process.

2.4.4 Design Justification Approach

Noble and Tanchoco [13] propose a design justification approach which requires economic justification at each design decision to ensure that a functionally and economically viable system design results from the process.. This method was intended to be applied to large systems design and concurrent engineering, but the principle is well suited for this design. The cost of each component of the design was evaluated concurrently with the design process, and its inclusion or rejection was decided at an early stage of the process.

2.5 Framework for the Design of the Virginia Tech Unit Load AS/RS

After evaluation of the different design methods, a combination of the Engineering Design and Design Justification methods was chosen as a framework for the design of the Virginia Tech AS/RS. The method is summarized as follows:-

Step 1: Definition of the problem: System requirements were defined by incorporating expertise from all parties which impact on the design, manufacture and use of the system. Important functional requirements of the system were defined.

Step 2: Develop possible design alternatives: Preliminary designs were generated using the models for travel times, workloads and utilization.

Step 3: Evaluation of alternative feasible solutions: Economic and engineering criteria were used to decide between alternatives.

Step 4: Detailed design specification: Complete system specification was formally defined, including performance requirements, economic justification, and conformance to the applicable engineering and system standards.

Step 5: Implementation: Components were manufactured or procured and the system was assembled the system on site. In order to speed the implementation process, some of the activities were scheduled to take place concurrently, to reduce project time of the whole project.

Step 6: Testing: The functioning of the AS/RS was evaluated in terms of its ability to satisfy stated performance requirements.

3. DESIGN OF THE VIRGINIA TECH AS/RS

3.1 Problem Statement

The most critical stage of any design process is the definition of the problem statement. Dieter [5] describes the formal definition of the problem statement as expressing as specifically as possible what the design is intended to accomplish. It must include the objectives and goals, written as a set of requirements which must be met. Any special technical terms or performance measures must be defined explicitly. Constraints placed on the design should be explicitly stated, and the criteria that will be used to evaluate the design should be established.

3.1.1 Design requirements

The fundamental need for this system is the storage and retrieval of material on pallets to and from the storage racks on the north wall of the laboratory. Pick-up and delivery of the loads to the FMAS is to take place at the intermediate staging conveyor interface, located at the end of the Shuttleworth conveyor system. The system must be capable of fetching or delivering a pallet in a minute or less. Travel speed should be approximately equivalent to the speed of the conveyor system. Pick-up and delivery transactions should be executed in 20 seconds or less. The maximum unit load size is specified as 20 pounds, to be loaded on the existing pallets. The system should be able to operate continuously for a maximum of four hours, at a throughput rate of up to thirty two single command transactions per hour. The project was proposed to be complete by November 1994. These requirements are summarized as follows:

- Storage and retrieval of pallets from existing storage racks on north wall of Laboratory.

- Pickup/delivery of loads is to take place at the intermediate staging conveyor interface.
- Cycle speed to allow for a maximum 1 minute per storage/retrieval transaction. Travel speed to be approximately the same as that of the conveyor handling system (250 ft/min.). Pick-up and delivery time to be less than 20 seconds.
- Unit load size: 20 lb., to be handled on the existing pallets (10" wide, 11" long, 5" deep).
- System was proposed to be completed by November 1994.
- Duty cycle: Throughput capacity for single command transactions of approximately thirty two loads per hour must be possible. Motors must be designed for continuous operation for a maximum of four hours duty in any one continuous period.

3.1.2 Constraints

Major constraints on the design of the system are the existing infrastructure, the time and cost to implement the system, and the operational safety requirements of the laboratory. The physical constraints are the requirement to serve the existing storage rack, the use of the existing pallet design, and the physical dimensions of the corridor space in which the AS/RS must operate. The cost of manufacturing the AS/RS should be less than $1200, which was made available to fund this project. Surplus equipment should be used where possible, to avoid unnecessary expenditures. The time constraint was set by the desired completion date of December 15, 1994. The AS/RS design had to comply with the safety requirements of the laboratory, the operating standards applicable to this class of equipment, and electrical wiring standards. The constraints are summarized as follows:

- Must service the existing storage rack, as installed on the north wall of the laboratory. Dimensions as specified in section 3.2.

- Unit load to be handled using the existing pallet design, as specified in section 3.2.
- Physical dimensions of the available space between the rack and the existing FMAS.
- Total cost of the system to be within the project budget of $1,200.
- Time to implement the project limited by the completion date: of Dec. 15, 1994
- Safety requirements of the laboratory must be complied with, as well as any other standards deemed applicable to this project.

3.1.3 Criteria

The success of the project was judged by its ability to satisfy the performance requirements of the system, as well as the ability to provide reliable operation during its intended service life. The cost to install the system is of prime importance, as funds for the project are limited. System functions should be simple to control, to reduce the complexity of system operational control. The life cycle cost should be kept to a minimum, by ensuring ease of maintenance, robustness of the design, and simplified logistic support. The AS/RS should build in sufficient flexibility to allow modifications to the hardware, and also to allow a variety of control strategies to be applied to the system. The physical appearance of the AS/RS should be in keeping with the aesthetics of the FMAS, and the laboratory environment. These design criteria are summarized as follows:

- Cost: to build and install the machine.
- Reliability of the system, as measured by availability or possible utilization rate.
- Speed of operation and throughput capacity.
- Ease of operation and control.

- Ease of maintenance, reflected by the ease of access to components, use of standard equipment and material types.
- Aesthetic appearance of system, in keeping with other industrial automation equipment in the laboratory.
- Flexibility of design and controls, to allow a variety of control strategies and software interfaces to be applied to the system.

3.2 Description of the Existing Infrastructure

3.2.1 Storage rack

Dimensions: The rack consists of 14 columns of eight storage locations. Each storage location is 10.5 inches wide, 12 inches deep, with heights of 6 inches and 12 inches, at different levels on the rack.. The lowest level (first level) is at a height of 2 feet 1 inch from the floor. The first two levels are 1 foot high, with the next seven levels being 6 inches high. There are thus 98 small storage locations, and 28 large storage locations. The clearance height to the top of the ninth level is 7 feet 6.5 inches.

Materials: The rack is constructed of 1 1/4" x 1 1/4" x 1/8" steel angle, fastened to columns of 1 1/4" square steel tube with steel screws, countersunk to ensure flush mounted surfaces, with no protrusions which could prevent smooth movement of the pallets. The same square steel tube is used to create an overhang for guiding the machine. This projects 14 3/4" in front of the rack face.

3.2.2 Pallets

The pallet design was created for use with the FMAS and remains unchanged. It consists of a 1 foot long, 10 inch wide, 1/4 inch thick plexiglass base, with stainless steel end pieces fastened by four set screws at each end. The end piece is 3 1/2" high, and includes an overhanging lip at each end, to be used to pull the pallet onto the ASRS.

3.2.3 Conveyor interface

The FMAS interface with the ASRS will provide a short length of conveyor between the entry and exit of the Shuttleworth Slip Torque Conveyor System. The Slip Torque system uses a frictional drive system, whereby the conveyor is driven continuously, with motion of pallets on the system being controlled at intersections by the action of pallet stops between the rollers, which are raised up at appropriate times to block the motion of the pallet. Transverse motion to the spurs is achieved by the action of pneumatically raised transfer belts. It was considered necessary to allow for an intermediate station between the conveyor system and the AS/RS, because the Slip Torque system does not allow pallets to come to rest at any point, without turning off the drive motors of the whole system.

3.2.4 Floor Space

There is a corridor approximately 3 feet wide between the storage rack and the FMAS. The crane is narrow enough to fit this space, and allow some clearance between the crane and any part of the existing rack and/or the FMAS.

3.3 Design of Major Components/Subsystems

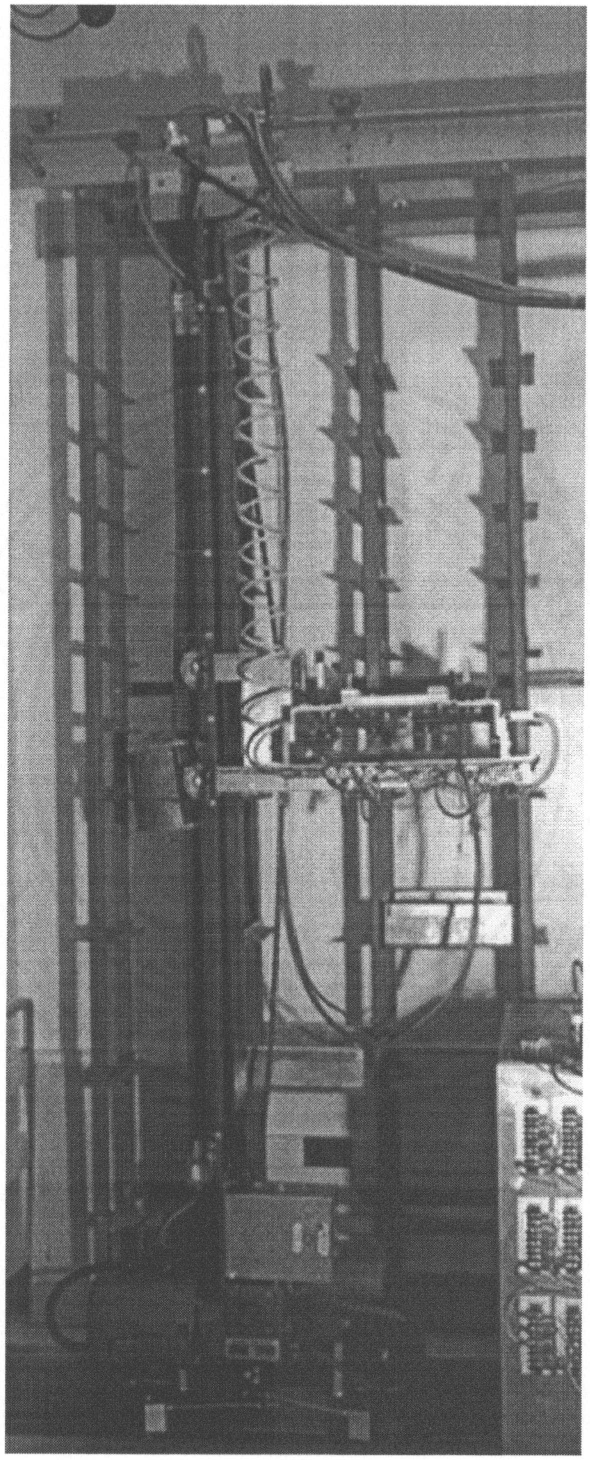

Figure 3.1: View of the AS/RS machine.

3.3.1 Horizontal drive

The main carriage runs on two polyurethane tired wheels on a steel rail fastened to the floor adjacent to the storage rack. Polyurethane was chosen to give quieter operating characteristics. One wheel is driven via a roller chain drive using a 1/2 horsepower, three phase AC gearmotor (see Figure 3.2).

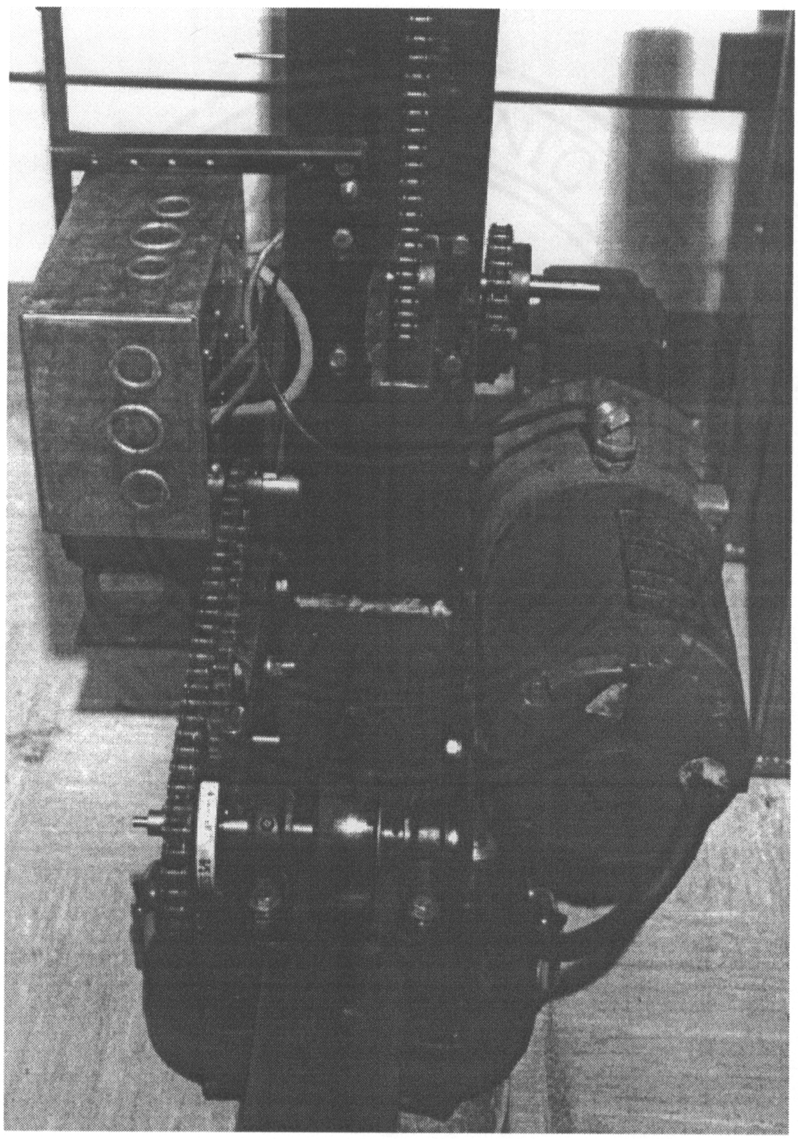

Figure 3.2: Horizontal drive arrangement of AS/RS

Speed control of the three phase AC gearmotors is achieved using a Toshiba inverter, which allows setting of various speeds, acceleration and deceleration rates, and emergency stopping. The inverter is placed in the main control cabinet, with relay switching of the three phase power in a control box on the crane. The other wheel runs free. Two sets of guide rollers mounted on the side of the carriage maintain carriage alignment on the rail (see Figure 3.2). The clearance between the guide wheel and the rail is adjustable, by the action of threaded guide-rods acting on pivoted wheel holders. The wheels are rubber tired steel wheels, with integral roller bearings. The load capacity of each wheel is in excess of 400 pounds.

Horizontal positioning of the crane is achieved through the use of variable sensitivity optical sensors, which use the vertical steel columns of the rack as targets.

3.3.2 Vertical drive

The vertical mast consists of T-section steel beam, with a unit-load handler and counterweight running on opposite sides, linked by roller chain. Vertical travel is driven by a 1/2 horsepower, three phase AC gearmotor (see Figure 3.3). Speed control is achieved using the same Toshiba inverter as the horizontal drive. In addition to the electronic speed control, there is an electro-magnetic disk brake between the motor and the reduction gearbox. This brake is interlocked with the power relays to ensure that the shuttle unit does not move unless powered, and to prevent the unit from falling away in the event of a power failure. The brake requires power (110 V AC) to release the drive shaft of the motor. The motor is interlocked such that it cannot be powered before the brake is released, as this would cause the motor to fail.

Vertical positioning of the shuttle is achieved using electronic optical sensors mounted on the shuttle side pieces. These detect calibrated markers mounted at each level of the rack, on a column adjacent to the mast.

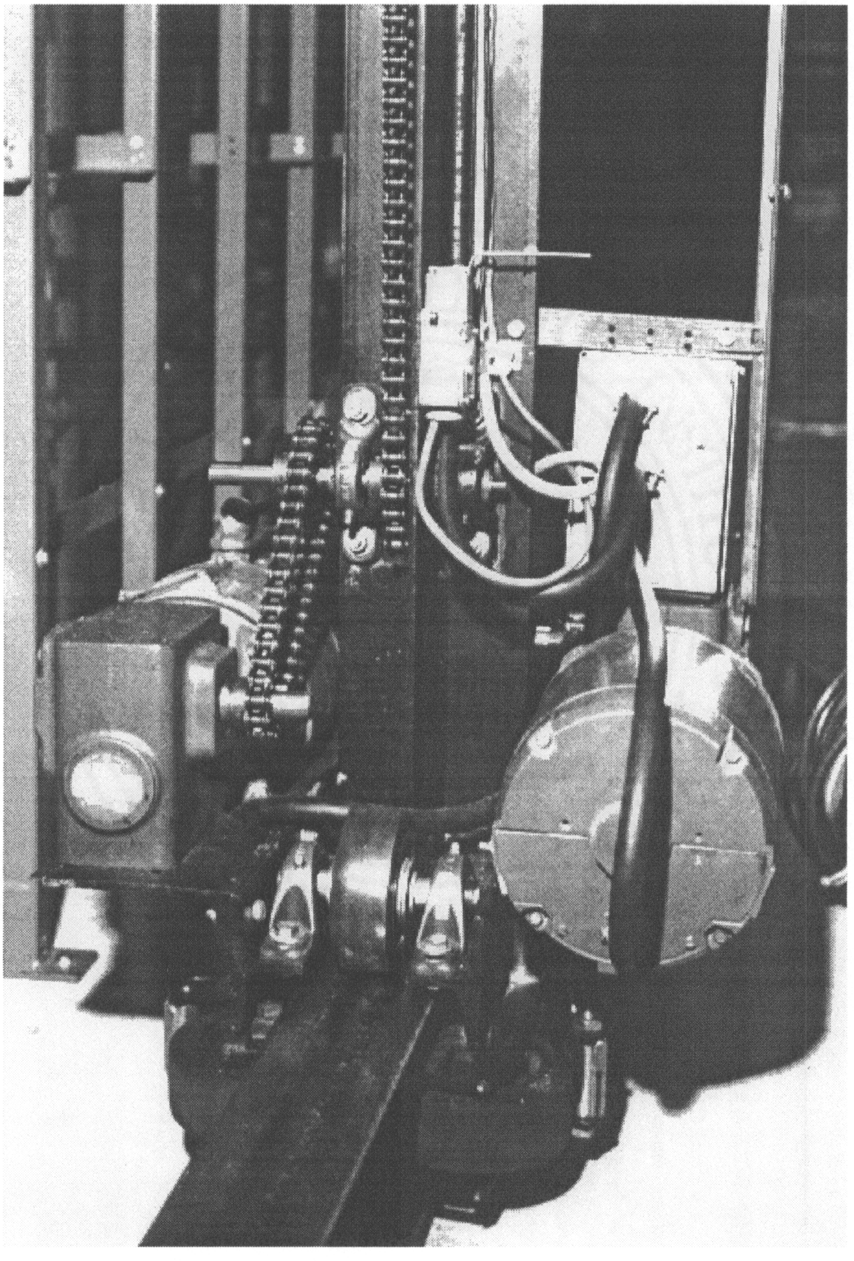

Figure 3.3 Vertical drive arrangement of AS/RS

3.3.3 Upper guide rail and power supply festoon

There is a short aluminum I-beam mounted transversely on top of the mast (see Figure 3.4). Four guide wheels are mounted on this beam such that the mast is positioned securely against a guide rail. The guide rail is fabricated from a section of a steel angle beam, and fastened to the rack overhang. An optical sensor is mounted adjacent to the guide wheels to detect calibrated markers at each vertical column division of the rack (as discussed for horizontal positioning of the crane).

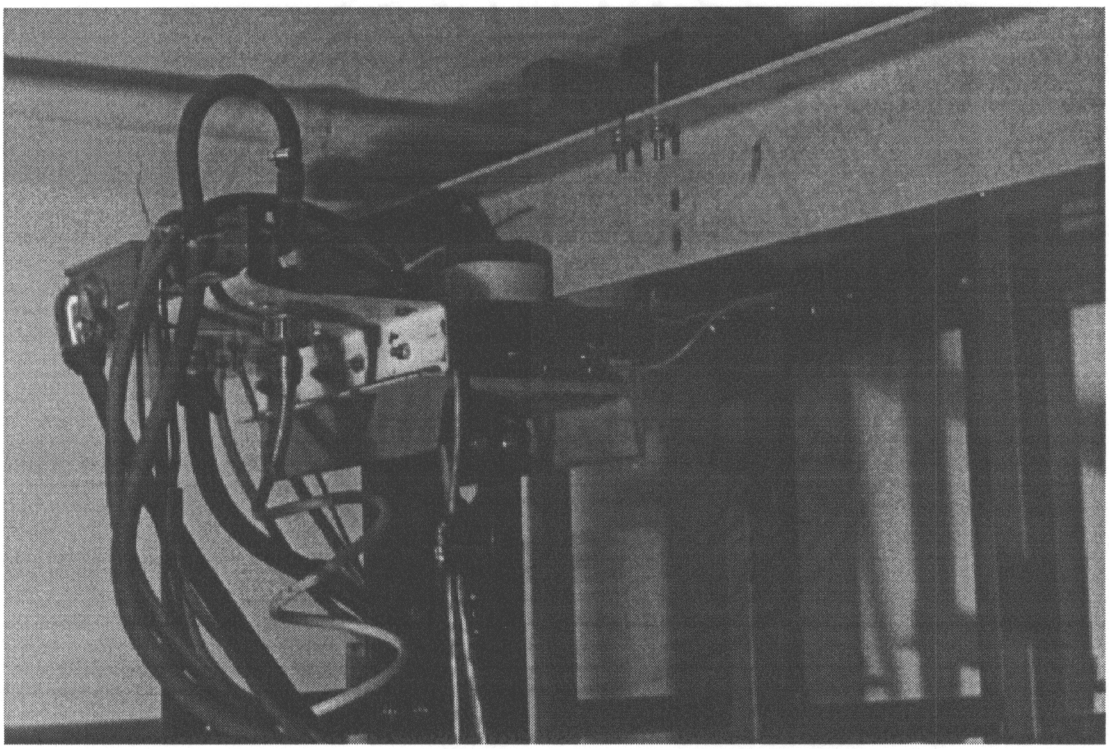

Figure 3.4: Upper guide rollers and festoon cables of AS/RS

The festoon cables are suspended from a point above the rack overhang, at the midpoint of the storage rack. These cables include the power supply for the main drive motors (three phase, 240 V AC), the power supply for the electromagnetic brake unit and power relays (110 V AC), the power supply for sensors, relays and the stepper motors for the shuttle drive

(24V DC), control wires for various sensors and electronic inputs (15 cores), and an air line for actuating the pneumatic cylinders for shuttle displacement. The cables are attached to the side of the mast head beam, projected out to one side to prevent fouling during crane motions.

3.3.4 Shuttle displacement

To allow sufficient clearance between the unit load handling device and the rack and or conveyor interface while traveling between pick-up and drop locations, a shuttle displacement mechanism was included (see Figure 3.5). This enables the shuttle to have a central traveling position, as well as a displaced position to the left or right, when the pallet is loaded or unloaded. The displacement is achieved by the action of two double acting pneumatic actuators, with electromagnetic control valves. The shuttle tray is mounted on roller bearing wheels, to allow the linear displacement from side to side. TEFLON guide plates are used on the sides and bottom of the tray, to facilitate easy movement of pallets onto the shuttle. These plates are adjustable to provide clearance for pallet motion, or for future adjustment for different pallet sizes, if needed.

3.3.5 Unit-load handler

Push-pull 'fingers' were mounted on special roller chain attachments. These are used to pull the loads onto the shuttle (at pick-up), and then to push the load off at delivery. The fingers are driven using a combination of roller chains and gear pinions (see Figure 3.5). They are driven using a SLO-SYN stepper motor mounted below the shuttle tray. The stepper motor is controlled by sending pulse inputs to a driver card, which in turn sends phased voltage to the stepper motor. The fingers on opposite sides of the tray are driven in reverse directions, using twin gear pinions connected to a single driving gear.

The shuttle carriage is mounted on the front face of the mast, with support wheels running on the front and back of the T-section beam. The wheels are made of polyurethane for quiet running on the steel mast, with integral roller or ball bearings. The clearance of the wheels is adjustable to account for differences in assembly, and for periodic adjustment to account for mechanical wear.

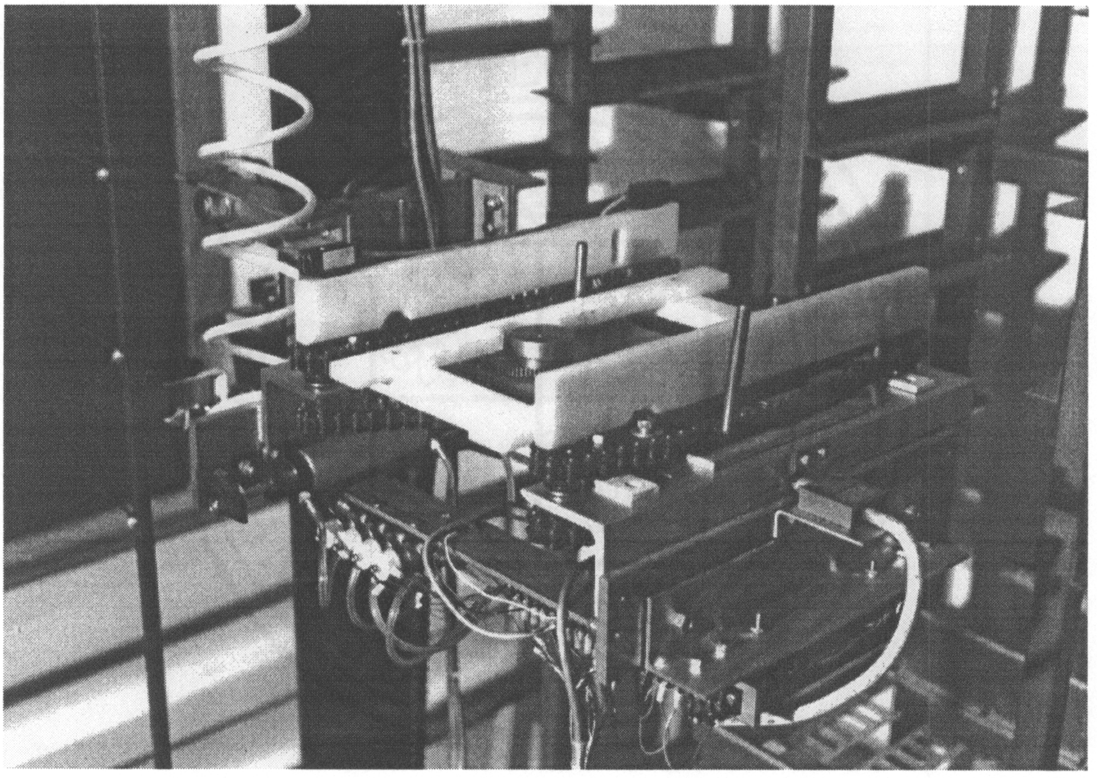

Figure 3.5: General arrangement of AS/RS shuttle and unit-load handler.

3.3.6 Sensors and safety limit switches

Mechanical limit switches are mounted at the top and bottom of the vertical travel, and at each end of the horizontal travel axis. These limit switches are interlocked with the drive motor power relays, to cut power to the motors if any of these final limits are reached. Emergency stop buttons are mounted prominently on the system, and similarly wired to cut power to the drive motors.

Mechanical limit switches are used to indicate the home position of the crane in both the horizontal and vertical axes. The home position is located at a point just above the lower final limit, and just to the rack-side of the left horizontal limit. This allows the crane to find home position before reaching the final limits, while always being able to use the same logic when traveling outwards from home. That is, it will never have cause to drive in the negative X direction beyond home, nor in the negative Y direction beyond home. At each start-up, it is envisaged that the initialization routine will include a return to home. From that point on, the controller will maintain the accumulating counters for positioning information, that is, to increment and decrement the counters as the crane moves away from, and towards home.

Variable sensitivity optical sensors have been used to detect vertical and horizontal positioning, and positioning of the pallet-handling fingers. By adjusting the sensitivity to make the sensors "short-sighted", the sensors provide reliable and accurate positioning information, without being influenced by other "targets" in their line of sight (but slightly further away). The sensors and/or targets have been mounted so that it is possible to adjust their positions relative to each other, to allow fine tuning of the alignment of the AS/RS relative to the storage rack.

3.3.7 Control system

System control will be accomplished using TI 565 PLC. The defining logic of system operation and interaction must facilitate using sensor inputs to the PLC to trigger output signals and states which will be used to drive motors. The major connector strips, DC power supplies and the Toshiba inverter are located in a stainless steel control cabinet at one end of the rack (see Figure 3.6). A Texas Instruments TI 435 PLC has been wired in to the control inputs for testing purposes, and remains a viable alternative for the control of the AS/RS. The design of the control program is beyond the scope of this project, although the typical programming requirements and capabilities of such devices have been considered throughout the design process. Control wiring has been documented and schematic wiring diagrams are included in Appendix 1 for information.

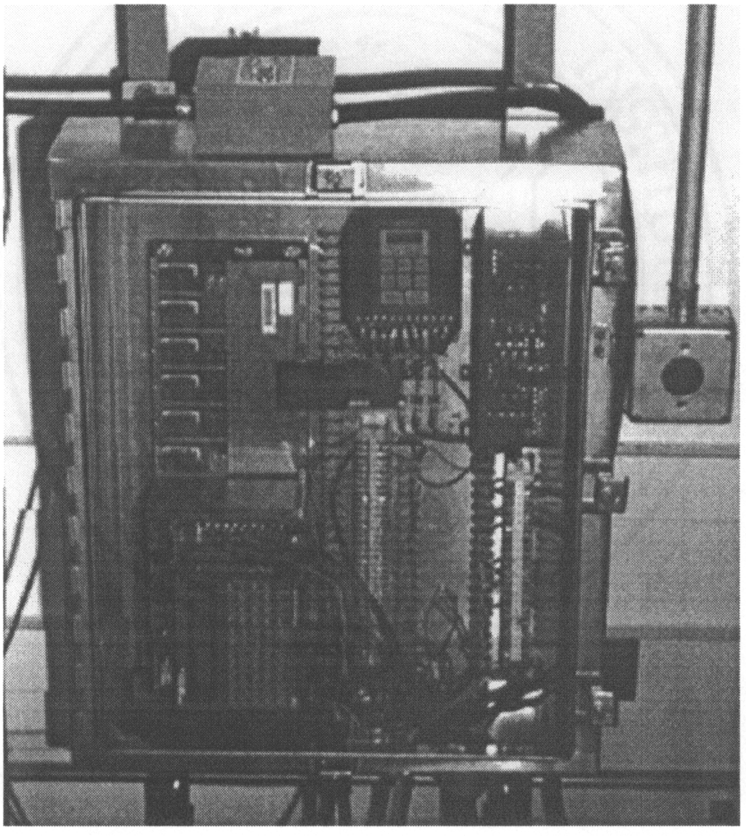

Figure 3.6: Control cabinet for AS/RS

3.3.8 Documentation

The completed design file for the AS/RS will include component drawings, or specifications and sources of supply, control wiring schematics, and operating instructions for the Toshiba drive controller and stepper motor drive controller card.

4. MODES OF OPERATION OF AS/RS

4.1 Horizontal and Vertical Travel

The Toshiba inverter controller is used to control the three phase drive motor for horizontal travel. This controller has variable settings for running speed, acceleration and deceleration ramp functions. It includes an emergency stop, normal stop, and jogging function (to incrementally advance the motor). The three-phase 230 V AC supply to the motor is further controlled by power relays in the small control box mounted on the machine. Power reaches the motors only when the solid state relays are powered by low voltage inputs from the PLC, and in turn switch on the 110 VAC power supply to the power relays. The circuit is arranged such that if one solid state relay (SSR) is powered, the horizontal travel motor receives power, and if the other SSR is powered, the vertical travel motor receives power. A further safeguard is the magnetic brake on the vertical travel motor. This device is actuated by 110 VAC, and is ON , i.e. braked, unless the vertical travel axis is powered. The brake was installed to prevent the shuttle from sliding down the mast under gravity while the motors are not operating. In order to prevent damage to the motor by attempting to drive it while the brake was engaged, the brake was electrically interlocked such that the drive motor power relay provides power to the vertical drive and disengages the brake. This ensures that the brake is released just before power is applied to the motors. A schematic of this wiring is included in Appendix 1.

Safety limit switches are installed at each end of the horizontal travel rail, and at the top and bottom of the vertical travel mast. These limit switches are interlocked with the motor power circuits, to disable power to the travel motors if the S/R machine reaches any of the limits. This safety feature is intended to prevent damage to the machine and surrounding infrastructure which might otherwise result. A further safety feature is a micro-switch which confirms that the shuttle tray is in the center position. The switch also serves as an interlock to the horizontal and vertical drive motors. This prevents the machine from moving while the tray is extended to either side, which could cause extensive damage to both the machine, and the pallets in the storage rack.

4.2 Positioning of the S/R machine

To monitor the postion of the machine while traveling, optical sensors are used in combination with targets mounted on the storage rack, and on the S/R machine. The optical switches are mounted on the shuttle assembly side beam (for vertical travel), and at the side of the upper guide wheel assembly (for horizontal travel). For detecting vertical travel, targets are mounted on a column adjacent to the S/R machine mast, aligned such that the shuttle will be level with each rack opening when the sensor is activated. Similarly, the upper section of the vertical columns of the rack are used as targets for detecting horizontal travel. These targets are aligned such that the left edge of the shuttle guide is in line with the left edge of the rack opening. This ensures consistent positioning of the shuttle relative to the pallets in the storage rack.

Description of the intended mode of control of storage/retrieval transactions is necessary to describe the functioning of the S/R machine positioning. The system will be initialized by confirming that the shuttle is at the vertical 'home' position, and that the S/R machine is at the horizontal 'home' position. The home position is situated to the left of, and below the first rack opening. As soon as the S/R machine begins moving away from the home position, the controlling PLC will maintain counters which will detect the number of targets which are passed during the travel motions. For reference purposes, travel away from home is considered positive, while travel towards home is considered negative. The accumulating counter for horizontal travel position should be incremented by one, for each target detected by the horizontal travel optical sensor while traveling in the positive X direction. When traveling in the negative X direction, the counter should be decremented by one for each target passed. An independent counter should be maintained in the same manner for vertical travel positioning. By keeping a reference of the current grid position, the controlling software will maintain knowledge of the position of the S/R machine relative to the storage rack. Valid rack positions would range from say (X,Y) = (1,1), to (X,Y) = (13,8), that is, each rack opening is specified by a unique grid reference. In order to move to a given location on the rack, the controller should determine the number of grid postions required to move, and in which direction, vertically and horizontally. The controller should then cause the machine to move the required number of blocks in whichever direction, using the last but one sensor input as a signal to ramp down in speed, and to run at crawl speed until the last target is detected. In this way, the device can use the higher speed capability of the motors, without over-running the desired position. This method has the advantage of using the same control logic for both vertical and horizontal positioning.

The system should be capable of retaining in memory, the last known position of the machine, in case of a power failure or system shutdown. This capability is important for system recovery, and re-initialization of the AS/RS.

4.3 Shuttle Position

The shuttle has a home position which is centered relative to the mast. This enables the machine to travel clear of the racks, pallet lips, and conveyor interface. Once the machine has come to rest in front of the desired rack opening, pneumatic cylinders operate to shift the shuttle to one side or the other, as decided by the controller. This motion is achieved by sending a control input (switch closure 24V DC) to the electro-pneumatic valves. For example, to move the shuttle to the right, valves 1 and 3 are opened, forcing both pneumatic cylinders to extend. To move the shuttle to the left, valves 2 and 4 are opened, forcing both cylinders to retract. For the shuttle to be locked in the central position, either valves 1 and 4, or valves 2 and 3 are opened, causing one cylinder to extend, and the other to retract. As stated previously, a micro-switch detects whether the shuttle is in the home (central) position, and it is electrically interlocked to prevent vertical or horizontal travel of the machine if the shuttle is not at the central position.

4.4 Pallet Movement

Pallet movement is enabled by the use of chain driven steel fingers which pull the pallets onto the shuttle, or push them off onto the rack or conveyor interface. Long fingers are used for pulling or pushing pallets (as long as the fingers are located correctly under the pallet lip), short fingers are only used for pushing pallets. The fingers are spaced such that they are at opposite ends of the shuttle as they pass the optical sensors. The chain is driven via a stepper motor which is controlled by a drive controller. This controller has inputs (5V DC switch closure) to control direction of rotation, and pulse input to control the number of steps to be advanced by the motor and the speed it will be driven. The position of the fingers is determined by optical sensors mounted at each end of the shuttle guide plate. The sensors are set at a height such that only the long fingers are detected (see Figure 4.1). The PLC will therefore get an input from each end, indicating the current position of the long finger. Depending on whether the machine is to load, or offload, a decision as to which direction to drive the motors must be made. In the control logic of the AS/RS, the pallet movement should only be initiated when all other motions have been terminated, and the shuttle is in line with the desired pallet location, or drop-off point.

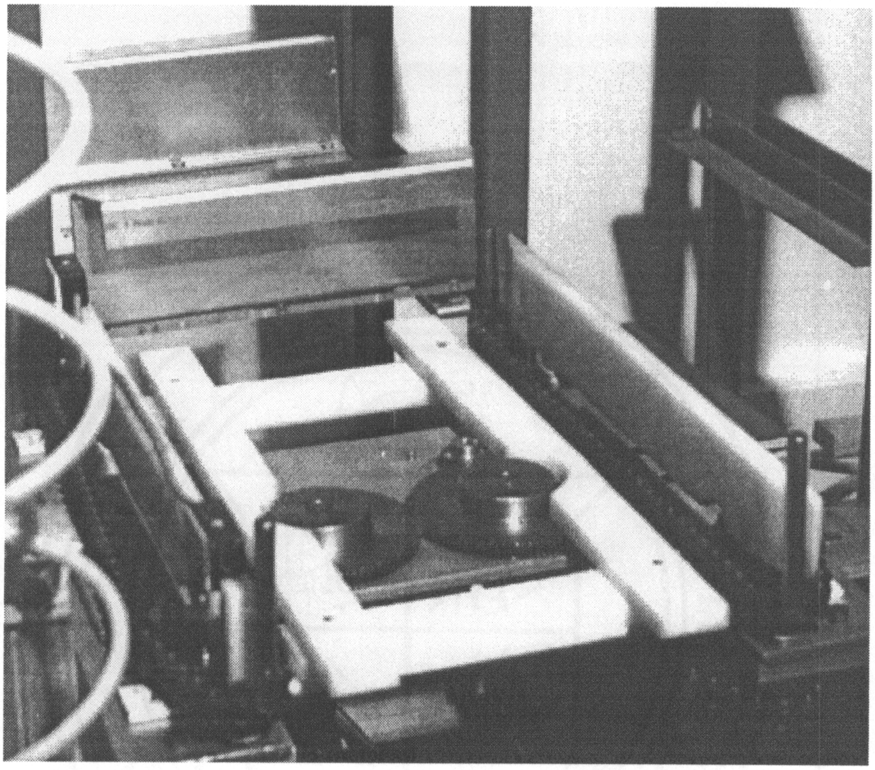

Figure 4.1: Initial position of fingers relative to pallet on unit-load handler.

Assuming that a pallet is ready to be picked up from the storage rack, long fingers would initially be positioned at the rack end. Once the shuttle has been extended to the rack, and is in-line with the pallet, pulse inputs from the PLC can be sent to the stepper motor driver to drive the stepper motor until the long finger reaches the other end of the shuttle. At this time the pallet will have been drawn fully onto the shuttle, ending up with the pallet pulled to the conveyor-interface end. The controller assumes this has taken place, and then causes the shuttle to move back to its home (central) position. Once this has been achieved, the next travel movement can begin.

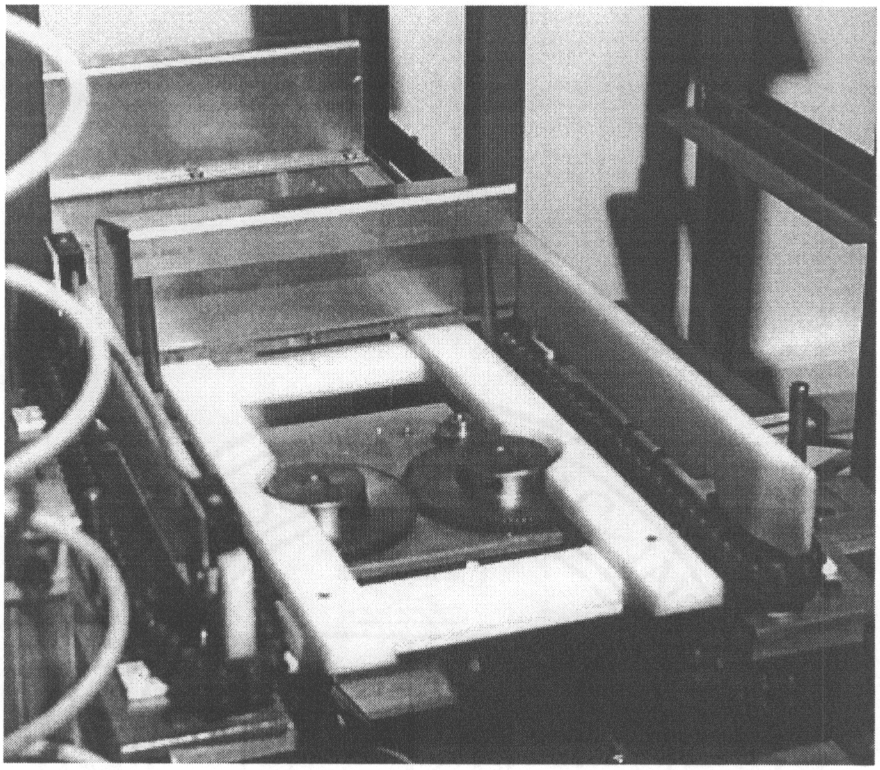

Figure 4.2: Pallet being pulled onto shuttle.

If for example, a pallet was being delivered to the conveyor-interface, the machine would move back to that position, and align the pallet guide in front of the delivery point. The shuttle would then be moved to that side, and then the controller could begin pulse inputs to push the pallet off, using the short fingers. Again, the PLC continues to drive the motor until it receives sensor input to indicate that the long finger has reached the other end of the tray guide, implying that the pallet has been pushed completely off the shuttle. If the AS/RS has prior knowledge of the next transaction, the pulling fingers could then be moved to the appropriate end of the shuttle, to be ready for the next transaction.

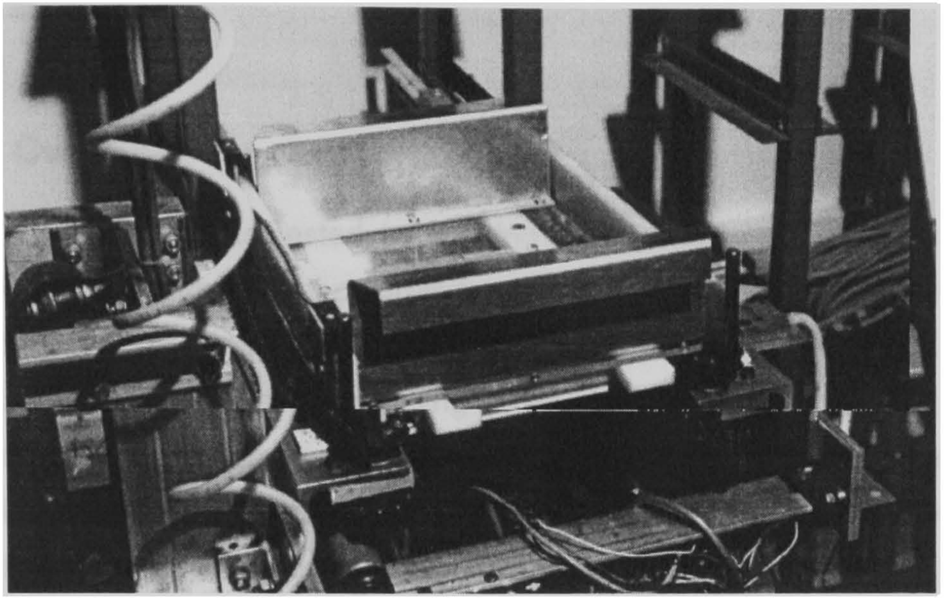

Figure 4.3: Pallet in its final position on the shuttle tray; note long fingers turned clear of pallet lip.

5. TESTING

5.1 Overview

The AS/RS was tested by running each component of the system individually, using the panel controls to control the Toshiba inverter, and the TI 435 PLC to provide the required output states to drive the control logic. The stepper motor was driven using pulse input from an electronic pulse generator, to simulate the pulse inputs which will eventually be provided from the PLC controlling program. These tests were video-taped to provide a record of the tests which would be convenient to review in committee.

5.2 Troubleshooting

During the testing phase, several problems were identified. These included a lack of clearance for the chain drive on the vertical travel drive, and some misalignment of the chain drive sprockets on the pallet-handler, which caused the shuttle-drive to jam. The vertical drive chain clearance was increased, and that problem was eliminated. A modification to the sprocket shafts and bearing mounts was implemented, which resulted in less frictional drag on the pallet drive. The pallet drive was then able to move loaded pallets, although it would be beneficial to purchase a more powerful motor for this function.

5.3 Operating range

The horizontal and vertical drive motors were driven at various speeds, using the Toshiba inverter to adjust the driving frequencies. The horizontal motions were driven at frequencies ranging from 5 Hz to 60 Hz, and the vertical motions were driven in a range from 5 Hz to 30 Hz. It is feasible to operate at higher speeds once electronic control is implemented, but this could not be operated safely using manual control. The speeds used for testing were in the correct range for the intended use of the machine.

6. CONCLUSIONS

6.1 Summary of the report

In this report, the need for the Automated Storage and Retrieval System to be added to the existing Flexible Manufacturing and Assembly System was introduced, and a brief description of the existing FMAS was given. The objective of the project was defined to be the design and construction of the hardware components of the storage and retrieval crane, as well as the conveyor interface. The design of the controlling software, and integration into the FMAS will be carried out by a subsequent project team.

A review of literature on automated storage and retrieval systems describes some of the important features of an AS/RS, and the operating characteristics which are to be expected of the AS/RS. Some general and specific guidelines for designing these systems were introduced, with specific reference as to how these guidelines were applied to this project. A design approach was selected, whereby cost justification of each design stage would be carried out, together with rigorous engineering evaluation of design components, in terms of their ability to satisfy the design requirements, constraints and criteria which were defined in the problem statement.

The design problem statement for the project was discussed and the preliminary design concepts for the system were then described. The detailed design was then described, with an explanation of the intended modes of operation of the AS/RS. Finally, tests were carried out to verify that the system is capable of satisfying the design requirements.

6.2 Design Performance

The performance of the AS/RS design should be judged by the design requirements, constraints and criteria described in Section 2. The AS/RS is capable of satisfying all of the load and speed requirements. Shortfalls are the current lack of the conveyor interface, and the failure to achieve the initial target date for completion of the project (November 1994). The time to complete the project was substantially more than anticipated, probably due to an over-optimistic view of the scope of the project. The conveyor interface is substantially built, but will require relocation of part of the existing conveyor to integrate it into the FMAS.

The design satisfies the infrastructure constraints in servicing the existing rack and pallets, using the narrow aisle between the FMAS and the rack. The project was implemented within the budget constraint, and conformed with all relevant safety standards for the laboratory.

In terms of the success criteria, the project was completed for a relatively small cost outlay (less than $ 800), by utilizing surplus and second-hand equipment, as well as some novel designs. The final product has been designed to perform robustly, and all components are easily accessible for maintenance. The system has been built using standard components for all of the main drive components, and allows for easy adjustment of clearances to take account of mechanical wear.

The AS/RS has also been built to be a flexible platform, allowing considerable possibilities for modification to the system if required. The simplicity of the controls makes for flexibility in the design of the control strategies, and also helps to improve overall system reliability. The main drive motors are capable of running at much greater speeds and distances than required, which may be useful to upgrade the system performance in the future. The appearance of the design is in keeping with other industrial equipment in the laboratory, and the system has been designed to run quietly.

6.3 Learning Objectives

The project has been an invaluable learning experience for the designer. Designing the system, procuring equipment, building and integrating the system has been difficult to achieve. It is much easier to design in the abstract than it is to actually have to piece together the finished artifact. The ease of access and maintainability requirement has been assured, by the number of times system components had to be stripped down and reassembled during the development of this prototype design. Another important lesson was in learning how to make use of the generous assistance and knowledge of my advisors and the ISE Manufacturing Systems Laboratory Staff. They have been extremely helpful in bringing this project to completion, as noted previously in the acknowledgments.

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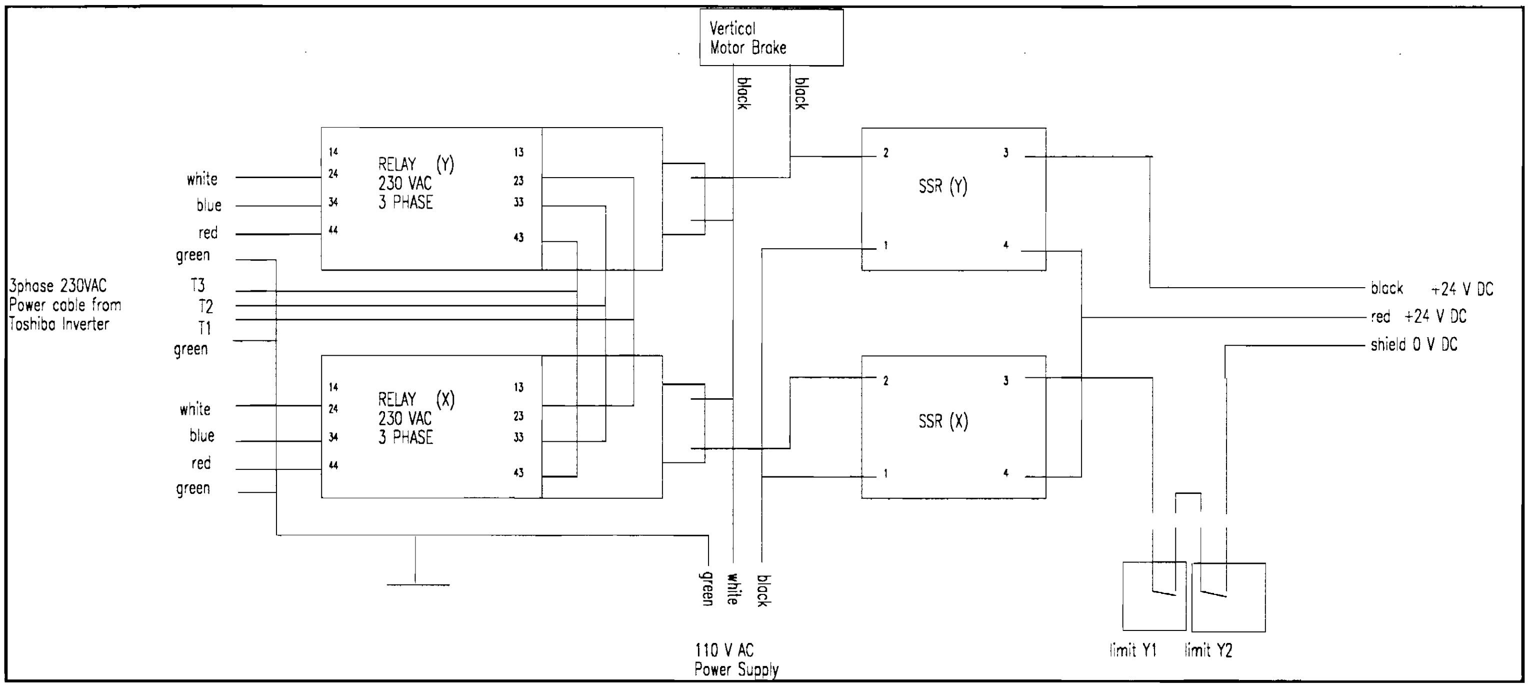
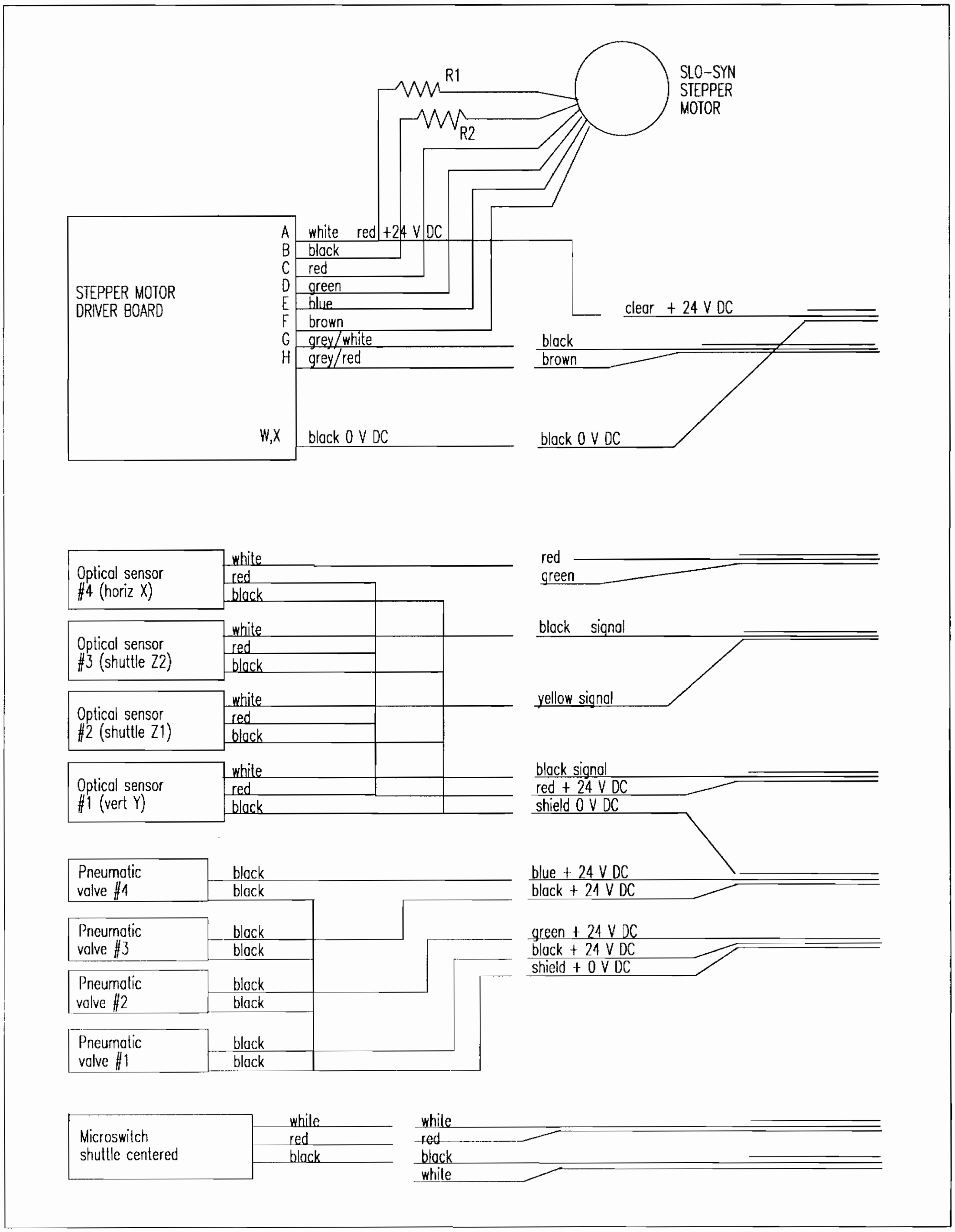
APPENDIX 1: Wiring Diagrams

Schematic of Power Relay Enclosure on S/R Machine



Schematic of Shuttle Wiring and Connections on S/R Machine



Schematic of AS/RS Control Wiring and Connections

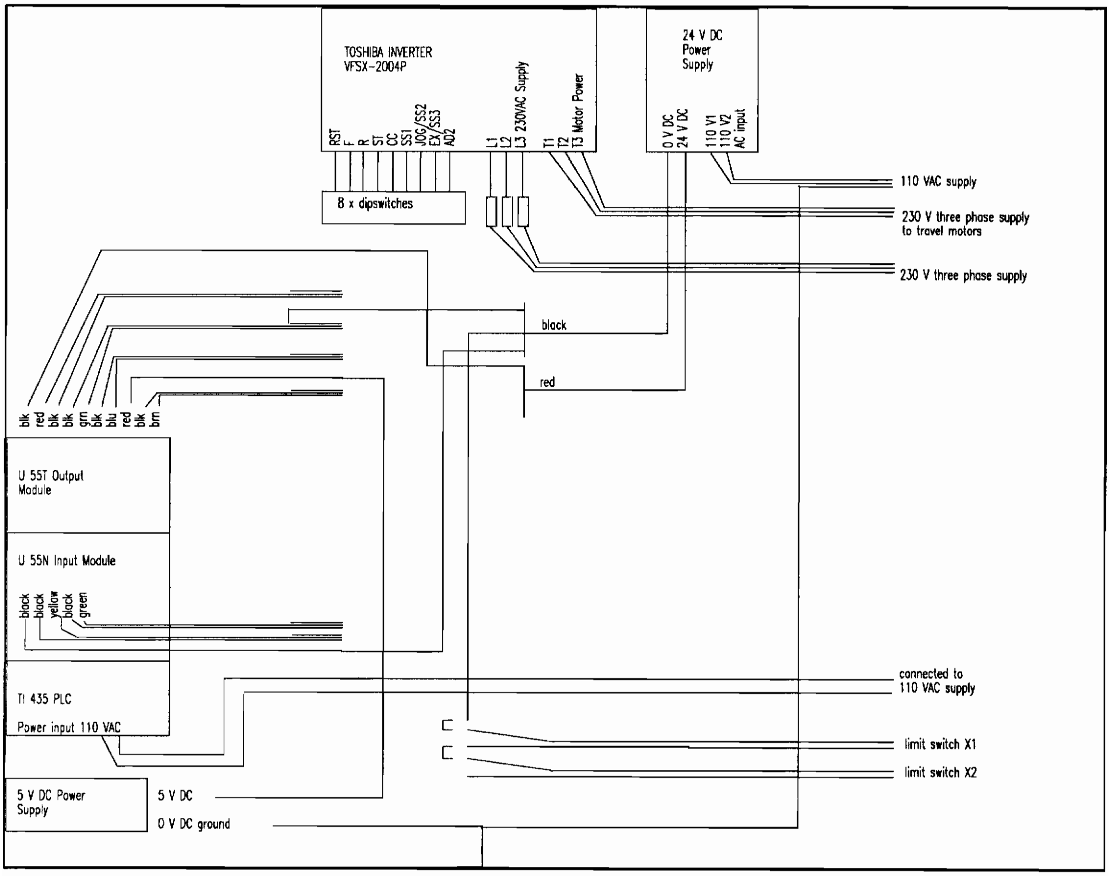


Table of AS/RS Connections

No.	Description	Volt.[V]	C/D	hase	Amp	Conn#	From...	Route	To...	Conn#	Colors	Ground
1	Mains Power: motors	230	AC	3	20	1	Breaker	Cable A	Tosh.Inverter	L1	red	
2						2				L2	black	
3						3				L3	blue	
4						G				G	green	green
5	Drive Motor Power	230	AC	3	20	T1	Toshiba In	Fest.cable B	AS/RS Relays	1	red	
6						T2				2	black	
7						T3				3	blue	
8						G				G	green	green
9	Motor Power	230	AC	3	5	VR1	AS/RS Rel	Cable C	Vert.drive moto	YM1	red	
10						VR2				YM2	black	
11						VR3				YM3	blue	
12						G				G	green	green
13	Motor Power	230	AC	3	5	HR1	AS/RS Rel	Cable D	Hor.drive motor	XM1	red	
14						HR2				XM2	black	
15						HR3				XM3	blue	
16						G				G	green	green
17	Mains Power: control	110	AC	1	15	L1	Socket	Cable E	Control Cabinet	N	blue	
18						L2				H	brown	
19						G				G	gr/yellow	gr/yellow
20	Power: control	110	AC	1	15		Conn.	Fest.cable F	AS/RS SSR's	SSR X	white	
21										SSR Y	black	
22						G				G	green	green
23	Power: motor brake	110	AC	1	15	L1	AS/RS SS	Cable G	Vert.motor brak	L1	black	
24						L2				L2	black	
25	Control: optical sensor 1	+24	DC		0.1		DC power	Fest.cable H	S/R machine		red	red
26	@vert.position Y	+0	DC				DC power				black	shield
27		+5	DC				PLC signal				white	black
28	Control: optical sensor 2	+24	DC		0.1		DC power	Fest.cable H	Shuttle		red	red
29	@shuttle.position Z1	+0	DC				DC power				black	shield
30		+5	DC				PLC signal				white	yellow
31	Control: optical sensor 3	+24	DC		0.1		DC power	Fest.cable H	Shuttle		red	red
32	@shuttle position Z2	+0	DC				DC power				black	shield
33		+5	DC				PLC signal				white	black
34	Control: optical sensor 4	+24	DC		0.1		DC power	Fest.cable H	Shuttle		red	red
35	@horiz.position X	0	DC				DC power				black	shield
36		+5	DC				PLC signal				white	red
37	Elec-pneumatic valve 1	+24	DC		0.1		DC power	Fest.cable H	AS/RS shuttle		black	black
38	@extend left actuator	0	DC								black	shield
39	Elec-pneumatic valve 2	+24	DC		0.1		DC power	Fest.cable H	AS/RS shuttle		black	green
40	@retract left actuator	0	DC								black	shield
41	Elec-pneumatic valve 3	+24	DC		0.1		DC power	Fest.cable H	AS/RS shuttle		black	black
42	@extend right actuator	0	DC								black	shield
43	Elec-pneumatic valve 4	+24	DC		0.1		DC power	Fest.cable H	AS/RS shuttle		black	blue
44	@retract right actuator	0	DC								black	shield
45	Stepper motor drive A	+24	DC		5		DC power	Fest.cable H	Stepper Motor		white	
46	B	24	DC								black	
47	C										red	
48	D										green	
49	E										blue	
50	F										brown	
51	CW Pulse G						PLC	Fest.cable H			grey/wh	black
52	CCW pulse H						PLC				grey/red	brown
53	W,X	0	DC		5							
54												
55												
56	Shuttle micro switch	24	DC		1		Microswitc	Fest.cable	PLC	...	black	bl-red=NC
57		24	DC		1						red	bl-red=NC
58		24	DC		1						white	bl-wh=NO
59		24	DC		1						green	green
60	Limit switch: mast top	24	DC	1	0.1		AS/RS	Fest.cable	Cabinet		Grey ext, shielded pai	
61	@NC-emergency stop											
62	Limit switch: mast bottom	24	DC	1	0.1		AS/RS	Fest.cable	Cabinet		Grey ext, shielded pai	
63	@NC-emergency stop											
64	Limit switches: left end	24	DC	1	0.1		Upp.guide	Cable	Cabinet		Grey ext, shielded pai	
65	@NC-emergency stop											
66	Limit switches: right end	24	DC	1	0.1		Upp.guide	Cable	Cabinet		Grey ext, shielded pai	
67	@NC-emergency stop											

APPENDIX 2: List of Expenditures

	Virginia Tech AS/RS: Inventory of Design Components					
	FUNCTION	DESCRIPTION	QTY	COST	AMT.	SOURCE
1	System Control:	TI 565 PLC, with analog module	1	$ -	$ -	ISE
		IBM PC	1	$ -	$ -	ISE
2	Horizontal Travel:	Reliance 230V AC 3 phase gearmotor: 1/2 HP	1	$ -	$ -	ISE
		AC Drive Controller: Toshiba VF-SX 20		$ -	$ -	see vertical travel
		Sprocket: 40B-10-3/4" bore	1	$ 4.21	$ 4.21	Invetech
		Sprocket: 40B-35-5/8" bore	1	$ 19.11	$ 19.11	Invetech
		Fafnir bearing housing SAK 1/2"	2	$ 14.70	$ 29.40	Invetech
		Fafnir bearing housing SAK 1/2"	2	$ -	$ -	ISE
		Sensor: Omron E3S-DS5 optical sensor	1	$ -	$ -	ISE
		Limit Switches: Mechanical	3	$ -	$ -	ISE
		Idling wheel:Moldon polyurethane 4"	1	$ 14.90	$ 14.90	Invetech
		Lower rail: beam C6 x 9 (20' required)	1	$ -	$ -	Va Tech surplus
		Upper rail: bar 1" x 1/4 x 20 ft	1	$ -	$ -	Va Tech surplus
		Lower guide rollers: 5" rubber/iron wheels	4	$ -	$ -	ISE
		Upper guide rollers:3.25" nylon & shafts	4	$ -	$ -	ISE
3	Vertical Travel:	Reliance 230V AC 3Phase Gearmotor: 1/2 HP	1	$ -	$ -	ISE
		AC Drive Controller: Toshiba VF-SX 20	1	$407.00	$ 407.00	Harmon
		Stearns Magnetic Disc Brake: 55,742 type	1	$ -	$ -	ISE
		Mast: Beam T5" x 15lb x 7.5 ft	1	$ -	$ -	Va Tech surplus
		Mast rollers: Nylon wheels with integral bearings	8	$ -	$ -	ISE
		Roller chain: RS 40-1/2" x 15 ft	1.5	$ 18.98	$ 28.47	Invetech
		Sprockets: 40B-18-5/8" bore	3	$ 7.28	$ 21.84	Invetech
		Sprocket: 40B-10-3/4" bore	1	$ 4.21	$ 4.21	Invetech
		Fafnir bearing housing SAK 5/8"	2	$ 14.70	$ 29.40	Invetech
		Fafnir bearing housing SAK 5/8"	2	$ -	$ -	ISE
		Chain connecting links (pack of 6)	1	$ 1.98	$ 1.98	Invetech
		Counterweight: 5" diam.steel shaft x 5" long	1	$ -	$ -	ISE
4	Shuttle Shift:	Pneumatic cylinder	2	$ -	$ -	ISE
		Pneumatic control valves and block	1	$ -	$ -	ISE
		Slide roller bearings	6	$ -	$ -	ISE
5	Pallet drive:	SLO-SYN stepper motor	1	$ -	$ -	ISE
		Stepper motor driver: 2D3128	1	$ -	$ -	ISE
		Gear: 1" pitch diameter	1	$ 14.00	$ 14.00	Invetech
		Gears: 4" pitch diameter	2	$ 28.58	$ 57.16	Invetech
		Sprockets:40B9-1/2" bore	10	$ 4.07	$ 40.70	Invetech
		Fafnir bearing housing SCJ 1/2"	2	$ 14.70	$ 29.40	Invetech
		Roller chain: RS-40: 1/2" x 6 ft	0.5	$ 18.98	$ 9.49	Invetech
		Special attachments: type M35	6	$ 1.20	$ 7.20	Invetech
		Sensor: Omron E3S-DS5 optical sensor	2	$ -	$ -	ISE
6	Miscellaneous:	Power cables: 60 ft	1	$ -	$ -	ISE
		Control cables: 60 ft	1	$ -	$ -	
		Emergency stop switches	2	$ -	$ -	ISE
		Enclosures/connector strips	4	$ -	$ -	ISE
		Pneumatic line, 1/4", 200psi, 25 ft	1	$ 10.85	$ 10.85	Invetech
		Bronze bushing	2	$ 3.00	$ 6.00	ISE
		Bolts, screws, nuts, washers	1	$ 25.00	$ 25.00	Heavener's
				TAX	$ 34.21	
				TOTAL	**$ 794.53**	

VITA

The author received his Bachelor of Science in Mechanical Engineering from the University of Witwatersrand in Johannesburg, in 1986. He subsequently worked for the South African Transport Services in Johannesburg and Pretoria, before taking a post with the South African Harbour Service in Durban. He worked as an engineering project manager, and then as Technical Manager responsible for maintenance of container handling equipment in the PORTNET Container Terminal, Durban. This report completes the requirements for a Master of Engineering degree which he started in August 1993. He is continuing to study at Virginia Tech, pursuing research in the economics of manufacturing processes.