SENSOR BASED REAL-TIME MECHATRONIC CONTROL OF COMPUTER INTEGRATED MANUFACTURING

Christopher Matlalo Kumile
B.Eng. (Hons), MSc. (Eng)
Mechatronics and Robotics Research Group (MR^2G) Laboratory
School of Mechanical Engineering
Durban, South Africa

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DECLATATION

I hereby declare that this entire thesis, unless specifically indicated otherwise, is my own original work, and has not been submitted in part or in whole for a degree to this University or to any other institution of Higher Learning. This thesis records the work completed by the author at the Mechatronics and Robotics Research Group (MR^{2}G) Laboratory, School of Mechanical Engineering, University of KwaZulu-Natal in Durban between October 1999 and June 2008.

I further declare that all sources cited or quoted are indicated and acknowledged by means of a comprehensive list of references.

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C.M. Kumile

Supervisor: Professor Glen Bright

ABSTRACT

Industrial competition is characterised by increasing globalisation of markets, coupled with networked manufacturing and diverse categories of buyers. Competition is ever increasing as markets undergo changes to brace for customer requirements. In the face of this situation where competitors are regularly ousted from the marketplace, companies are compelled to be one step ahead in launching innovative products to the market. As a result, technology and product life cycles are shortened. In order for the manufacturing system to survive changes in this environment, its control system must be flexible and reusable in order to adapt to changed conditions, either automatically or with only minor changes necessary. Mechatronics has recently emerged as one of the attractive philosophies for rapid product design and development into the volatile market.

Mechatronics has been described as the ***synergistic*** combination of mechanical engineering, electronics, controls engineering, and computers, all ***integrated*** through the product design process. This project proposes the design and development of a Mechatronic Sensory System (MSS) that could be used to enable efficient operational tasks in Computer Integrated Manufacturing (CIM) systems.

The MSS has been developed as a flexible, PC-based technology that implements a series of infrared (IR) emitter and receiver sensors strategically placed along the conveyor and single scanner sensor system. These emitter and receiver sensor pairs enabled the conveyor segment operation as well as tracking and exact positioning the pallet on the conveyor belt. The single scanner sensor was used to automatically capture data from the shop floor utilising machine-readable bar code system. Information from multi-sensors is fused to ensure optimal operation of the CIM shopfloor control system.

This dissertation presents the design of a MSS apparatus that can be used to achieve affordable cost shop-floor control system of a CIM cell with improved flexibility and reconfigurability.

DEDICATION

This thesis is dedicated to:
My wife, Violet Gobona;
My daughters, Tsholofelo Seele and Wazha Matlhogonolo;
My sons, Mbakiso Christopher Junior and Kago
My parents, and;
My parents -in- law.

"It is not the strongest of the species that survives, nor the most intelligent, it is the one that is most adaptable to change"

By Charles Darwin {1809 – 1882}

ACKNOWLEDGEMENTS

This thesis is the result of many years of research at the Mechatronics and Robotics Research Group (MR^{2}G) laboratory, School of Mechanical Engineering, University of KwaZulu-Natal, Durban. Although many aspects of the work have largely been conducted independently, I have, over the years, had the opportunity to work closely with many and most helpful people at the laboratory. I would like to take this opportunity to express my gratitude to all those who helped me make this thesis a reality.

This thesis could not have been possible without the help and encouragement of my supervisor, Professor Glen Bright. I am thus greatly indebted to him for his constructive guidance and encouragement during undertaking the research. He has provided me with academic counselling and encouragement throughout my research.

I would like to also thank:

- My then colleagues at MR^{2}G laboratory, Dr. J Potgieter, and Dr. N S Tlale for their suggestions and constructive criticism which was extremely helpful during the execution of the research project;

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TABLE OF CONTENTS

Chapter 1 INTRODUCTION

Chapter 2 CIM MECHATRONICS BASED SYSTEMS

Chapter 3 THE DESIGN OF A MECHATRONICS SENSORY SYSTEM

Chapter 4 MR^{2}G CIM CELL COMPONENTS

Chapter 5 MECHATRONIC SENSORS AND SIMULATION TOOLS

Chapter 6 ACTUATION OF THE MSS APPARATUS

Chapter 7 FEEDBACK AND PC BASED CONTROL OF MSS APPARATUS

Chapter 8 PERFORMANCE ANALYSIS OF THE MSS APARATUS

Chapter 9 OPERATIONAL REVIEW OF THE MSS APPARATUS

Chapter 10 CONCLUSIONS AND FUTURE RESEARCH

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

For the convenience of the reader, here follows a list of acronyms and abbreviations used throughout the thesis:

ADCS:	Automatic Data Capture System
AGV:	Automatically Guided Vehicle
AMICE:	European Computer Integrated Manufacturing Architecture
ASRS:	Automated Storage and Retrieval System
BIS:	Business Information System
2D:	Two dimensional
3D:	Three dimensional
ANSI:	American National Standards Institute
APT:	Automatically Programmed Tool
CAAP:	Computer Assisted Assembly Planning
CAD:	Computer Aided Design
CAE:	Computer Aided Engineering
CAM:	Computer Aided Manufacturing
CAPP:	Computer Aided Process Planning
CAR:	Computer Aided Robotics
CAT:	Computer Aided Tolerancing
CCS:	Cell Co-ordinate System
CE:	Concurrent Engineering
CIM:	Computer Integrated Manufacturing
CIM-OSA:	Open Systems Architecture for CIM
CMM:	Co-ordinate Measuring Machine
CNC:	Computer Numerical Control
CP:	Continuous Path
CPV:	Continuous Process Variations
DES:	Discrete Event Simulation
DFA:	Design for Assembly
DFx:	Design for x (assembly/manufacture/….)
DOF:	Degree of Freedom
ERP:	Enterprise Resource Planning
FIFO:	First in first out

FMS:	Flexible Manufacturing Systems
ISO:	International Organization for Standardization
LAN:	Local Area Network
LIFO:	Last in first out
MAP:	Manufacturing Automation Protocol
MES:	Manufacturing Execution Systems
MSS:	Mechatronic Sensory System
NC:	Numerical Control
NGMS	New Generation Manufacturing Systems
NIST:	National Institute for Standards and Technology
OLP:	Off-line Programming
PES:	Photo-Electric Sensors
PDES:	Product Data Exchange Specification
PMU:	Physical Mock-up
QFD:	Quality Function Deployment
RCS:	Robot Control Software
RMS	Reconfigurable Manufacturing System
RRS:	Realistic Robot Simulation
SF:	Sensor Fusion
SPC:	Statistical Process Control
SQC:	Statistical Quality Control
SFCS:	Shop-Floor Control System
STEP:	Standard for the Exchange of Product Model Data
TCP:	Tool Centre Point
VWD:	Virtual Manufacturing Device
WCS:	World Co-ordinate System

Chapter 1

1 INTRODUCTION

1.1 Introduction

In this chapter, generic manufacturing requirements, characteristics, and some definitions of mechatronics and sensory systems are provided. A motivation for the research is given and an overview of the contents and structure of the thesis is also provided.

1.2 Requirements on Manufacturing Systems

There is an increasing demand, due to globalisation, for manufacturing systems to be able to be re-configured quickly to accommodate new varied products, utilising new machines or processes. Nowadays businesses are pressured to deal with increased complexities and challenges of customers demanding high quality, low cost products, higher product variety, small batches and shorter throughput times. Various strategies have been employed in order to enhance the competitiveness of businesses, these include, but not limited to; agile manufacturing, computer integrated manufacturing, reconfigurable manufacturing, automation and mechatronics. Modern industrial companies face an increasing need to adopt changes to meet the demands of the customers in the competitive environment. Manufacturing system (MS) as shown in Figure 1.1 is a collection of operations, processes and humans devoted to the transformation of raw materials into useful goods and services. The MS converts raw materials through the utilisation of equipment, energy, labour and input market information into output goods and services. There is an occasional scrap and waste that is produced and this information is fedback to the input side of the system for continuous improvement of manufacturing system's performance. Manufacturing today occurs in an environment in which there is fierce competition within the global market. The government regulatory mechanisms and socio-economic environment must be conducive for direct foreign investment into the manufacturing industry. Entrepreneurs engaged in manufacturing must be cognisant that competition erodes both their inputs and their customer base.

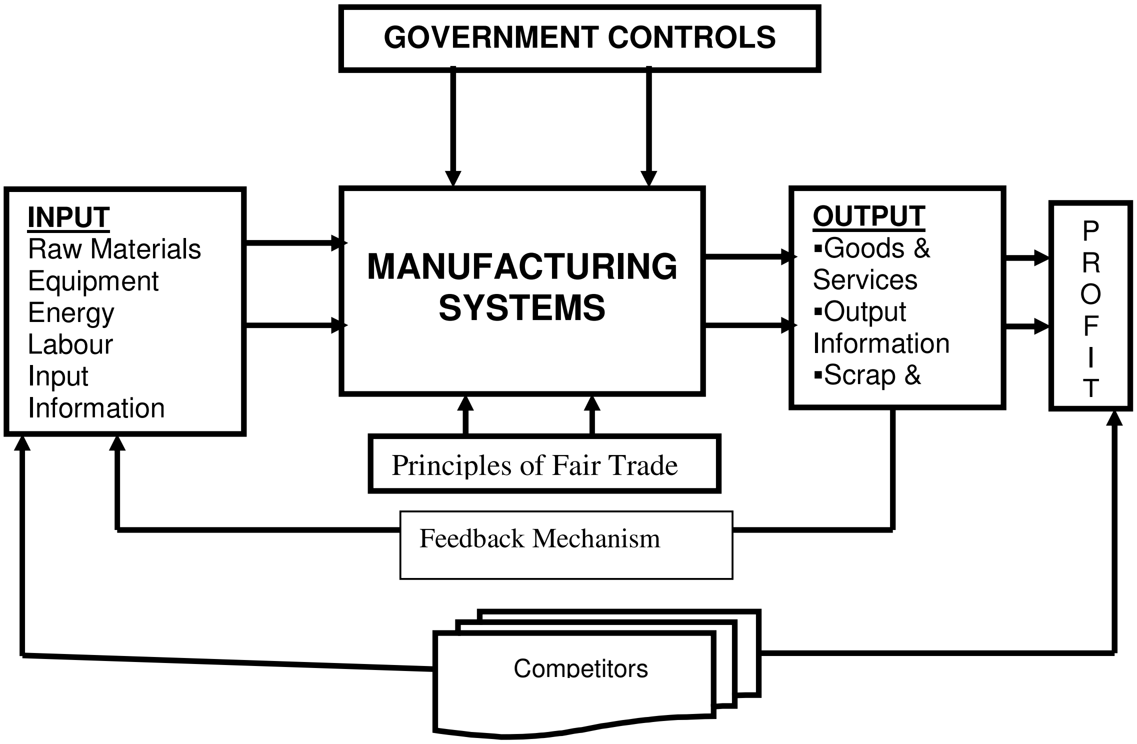


Figure 1.1 Manufacturing System in a Competitive Environment

There are two drivers for the advancement in products and manufacturing systems (Olsson and Pianni). First, there is a *technological push* from the availability of advanced information and communication technology and research results. Secondly, there is *demand pull* from competitive factors – increased competition on the global markets puts pressure on manufacturing industry to reduce costs, shorten time-to-market, and enhance quality.

Today, customers take high product quality and low costs more or less as inherent characteristics of products. Instead, competition is based on factors like product customisation, time-to-market, and delivery services. Because of this, there is an increasing demand on manufacturing industry to be able to re-configure its manufacturing systems quickly in order to handle new products, whilst using new machines or processes.

1.3 Market Demands on Flexibility, Quality, Cost and Time

The design and operation of manufacturing systems to a great extent are affected by the set of products manufactured. It is now evident that the era of mass-production has been replaced by the era of market niches. The era of market niches can be described as key to creating products that can meet the demands of a diversified customer base in short development time, low cost, high quality, and production capacity [Gullander]. This makes *flexibility* an important attribute of manufacturing [Chryssolouris]. The challenge is to be able to combine high level of automation with high-level flexibility. In other words, applications are needed that can easily be adapted when required by changes in the environment. This means it must be easy to re-configure the manufacturing system in order to manufacture new products or product variants, possibly using new machines or processes.

Another very important aspect in a situation of highly competitive markets is *quality* [Bodur et al]. Quality is a dynamic measure and is governed by product quality which is determined by the production system.

Manufacturing industry seeks to improve its competitiveness through quality improvement, reduction development time and cost. These are sometimes considered as aspects that determine the quality, but in this thesis there are treated separately. Some of the time needed to develop and manufacture a product is governed by the time and cost of developing and operating the manufacturing system. Manufacturing systems that can easily be made to manufacture new products and product varieties therefore are of high importance. Future manufacturing systems must be affordable, easy to develop, install, learn, operate, and maintain.

1.4 Human, Strategic and Economic Demands

System design and implementation are not only governed by technological requirements and market demands, but also must take into account demands made by people working with the system as well as economic and strategic demands. These demands may indirectly be caused by technological and/or market demands.

Bodur et al. has categorised manufacturing environments into the following main types; see Figure 1.2:

- *Make to Stock* (MTS): Products are manufactured against well-known and predictable demand mixes. This manufacturing environment has the advantage of quick delivery but the draw back is loss of sales due to unknown demand and stock outs. Life cycles of products are relatively long and predictable.

- *Assemble to Order* (ATO): In this environment products are made by the assembling of sub-assemblies into a final product that fulfils customer requirements and demands. Delivery times are of medium length and depend of available sub-assemblies. Assembly only takes place when order is received. The main advantage of this manufacturing type is that there is no need for final storage of finished products and the disadvantages are that the customer has limited influence on the product design and forecasting is difficult.

- *Make to Order* (MTO): Activities in this environment are characterised by high uncertainty since products are often one-of-a-kind and the sales volume are difficult to forecast. Products are customised to specific customer needs. The final product is specified by exchanging information between customer, sales, and engineering activities. As a result, lead-times range from medium to long.

- *Engineer to Order* (ETO): This manufacturing environment is an extension of the MTO environment. Product specifications are mainly based on customer specifications. Products are one-of-a-kind and are engineered to order. Companies organised in this manner have no stock of finished products and every order is engineered as needed.

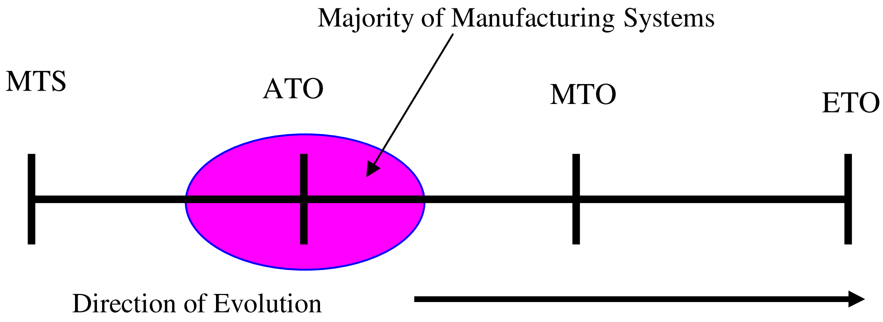


Figure 1.2 Evolution of Manufacturing Systems

Automated manufacturing systems (AMS) are an important development of the new millennium. The development of versatile computer numerically controlled (CNC) machine tools has significantly increased the productivity of the manufacturing industry by decreasing set-up and machining times and by minimizing the human error involved in the manufacturing processes. The era of mass production has been replaced by mass customization using Computer Integrated Manufacturing (CIM) systems. With the advance of computer and information technology, it became feasible to integrate isolated automated machinery with centralized or distributed computer control and database systems. Improved networking technologies and the Internet has enabled companies to integrate very large-scale systems and accept highly customized orders online from all over the world. This high level of product customization requires very flexible and yet efficient manufacturing systems, which are comprised of seamlessly integrated operating manufacturing units.

1.5 Research Project Scope and Goal

The scope of this research addresses the fields of advanced manufacturing technologies; specifically control systems and applied synergistic mechatronics design to develop the MSS apparatus. The MSS apparatus was designed to be integrated into the CIM cell being developed at the Mechatronics and Robotics Research Group (MR^2G) Laboratory, School of Mechanical Engineering at the University of KwaZulu- Natal, Durban, South Africa. The MSS apparatus needed to be a PC-based technology, efficient whilst having affordable developmental costs.

The operation aspects of the MSS in adding to the flexibility of the Shop-floor Control System (SFCS) of the CIM cell are highlighted as it can control processing workstation tasks by performing planning, scheduling, and execution functions.

The goal of this research project is to present models and procedures required for the development of MSS within the operation of a CIM cell, integrated with artificial intelligence technology to realise system synchronisation, real-time data acquisition and signal processing.

1.5.1 Research Project Objectives

The specific research project objectives are:

- Research modelling and simulating all CIM cell components at MR^{2}G laboratory such as the robot, computer numerical control mill, automated guided vehicle, automated storage and retrieval system, coordinate measuring machine, conveyor belt and the automated visual inspection system;

- Research and development of an experimental set-up consisting of CIM components equipped with sensors interfaced to a computer based architecture control system to enable real-time data acquisition, computational and signal processing;

- Research and development of the Automatic Data Capture System (ADCS) using the bar code and sensory systems within the CIM cell;

- Research and development the sensory system and its interaction with the shopfloor multi input- output adaptive controller to operate the CIM cell in dynamic environments;

- To fuse and integrate multi-sensory data to enhance the operation of the CIM cell Shop-floor control system (SFCS);

- Determining experimentally the performance of the MSS apparatus within the CIM cell process. This includes: conveyor speed, object recognition and inspection system, material handling and processing;

- Validation and verification of theoretical models with experimental research results.

1.6 Research Project Motivation

Manufacturing Control systems in today's industry have inter-related characteristics such as:

- Elongated system development time and maintenance, which culminates to more costs;
- Poor quality in that its functions, behaviour, or properties do not correspond to actual needs;
- SFCS often lacks enough flexibility to be reconfigurable to adapt to the increasingly frequent changes required as a result of rapid developments in technology, products, and machining and assembly processes.

1.7 Research Publications

The following papers have been presented at various conferences and journals (both local and international) during the execution of this research project:

(i) *"Modelling and Development of a Real-time Mechatronic Shop-floor Control System for Computer Integrated Manufacturing",* **C.M Kumile**, Glen Bright, The 7th Mechatronics Forum & Biennial International Conference, Atlanta Georgia, USA, 6-8 September 2000.

(ii) *"Sensor Based Control of Computer Integrated Manufacturing",* **C.M Kumile,** Glen Bright , The 8th Mechatronics Forum & Biennial International Conference, University of Twente, Enschede, Netherlands, 24 – 26 June, 2002. (see http://www.rt.el.utwente.nl/mechatronics2002/)

(iii) *"Real-Time Sensor Based CIM Control Architecture",* **C.M Kumile**, Glen Bright, The 18th International Conference on CAD/CAM, Robotics and Factories of the Future 2002 (CARS & FOF 2002, 3 – 5 July 2002, Porto, Portugal. (see http://www.inescn.pt/~cars-fof/site-index.htm)

(iv) *"Model Based Control of CIM using Mechatronic Sensory Systems"*, **C.M Kumile,** Glen Bright, International Conference on Mechatronics 2003, 26 –27 June 2003, Loughborough, United Kingdom. (http://www.mechatronics.org.uk/icom/)

(v) *"Sensor Based Control Systems for Computer Integrated Manufacturing Systems"*, **C.M Kumile**, Glen Bright and N.S Tlale, The 23rd ISPE International Conference on CAD/CAM, Robotics and Factories of the Future 2007 (CARS & FOF 2007), 16 – 18 August 2007, Bogota, Columbia.

(vi) *"Sensor Fusion Control System for Computer Integrated Manufacturing"*, **C.M Kumile**, Glen Bright, South African Journal of Industrial Engineering May 2008, ISSN 1012277X, Volume 19, issue 1, Pages: 179-194.

1.8 Contribution to New Knowledge

The research discussed in this thesis makes a meaningful and original contribution research in the field of mechatronics, shopfloor control system and the utilisation of multi-sensor data fusion concepts in the current global competitive manufacturing environment. The main contributions to new body of knowledge of this thesis are the following:

- The development of MSS concepts as an affordable automation solution to provide efficient control and operation of a CIM cell;
- Provision of a rapid and integrated way to develop a distributed SFCS and a set of formal models with a simple and structured way to the specification in the context of a distributed SFCS.
- Enhancements of optimized system modelling, consisting of the component libraries, system validation and verification in real-time simulation.

1.8.1 Industrial Relevance

Companies are faced more by customers demanding high quality products which have to be delivered within short lead-times as well as being highly reliable whilst not costly. The technological developments in communication provide Electronic Data Interchange (EDI) that enables a faster and more accurate response of a CIM system to customer demand. The proposed MSS apparatus will have an impact on the choice of the operational system.

There is also an impact on performance and throughput times that can be realised. Therefore the research is highly relevant to the design of the SFCS in scheduling within CIM environment and in a broader perspective for meeting customer demands.

1.9 Assumptions

The following assumptions and conditions were made prior to undertaking the research:

- The manufacturing system under consideration is a discrete part manufacturing system.
- The scope of the manufacturing processes is restricted only to machining, excluding inspection and assembly/disassembly.
- The control system under consideration is intended to operate with automated equipment such as CNC machines and robots.
- Capacities of material processors (machines) and material handlers (robots) under consideration are one at a time. All movement of parts requires material handlers.
- The machined parts are of prismatic types, whose material removal features can be processed by a minimum of 3 -axis milling machines.

1.10 Thesis Layout

The remainder of the thesis is organised as follows:

Chapter 1: This chapter provides the background of the project as well as the problem statement. The research scope and aim are derived as well as research objectives are formulated. The chapter also presents the delimitations that have been set for this thesis, and finally the outline of the thesis is presented.

Chapter 2: This chapter provides literature survey on the research matter, introduces fundamental ideas and concepts regarding mechatronics systems as well as their design. The designs of current CIM technologies are also considered and examined closely.

Chapter 3: This chapter presents the conceptual designs and the final design and development of the proposed MSS apparatus for the CIM Cell to provide for real-time data acquisition and signal processing.

Chapter 4: This chapter provides a detailed description of components developed to constitute the MR^{2}G CIM Cell test bed in which the MSS apparatus were tested.

Chapter 5: This chapter provides a review of sensors, modelling & simulation systems used in CIM technologies.

Chapter 6: This chapter presents the mechatronic actuation of the MSS apparatus and the execution of equipment controllers utilised in the proposed sensory system.

Chapter 7: This chapter provides a PC based control of the MSS apparatus to provide for real-time data acquisition and signal processing.

Chapter 8: This chapter discusses the performance analysis of the proposed MSS apparatus encapsulating both the experimental and simulated results.

Chapter 9: This chapter provides an operational review of the MSS apparatus within the CIM cell.

Chapter 10: This chapter summaries the most important parts of the thesis, provides some discussions and proposes directions for future research in this exciting field.

Chapter 11: This chapter provides the reference and bibliographic material used during undertaking this research project.

1.11 Chapter Summary

This chapter has provided an overview of generic manufacturing requirements, characteristics, and some definitions of mechatronics sensory systems. A motivation for the research has been articulated and an overview of the contents as well as the structure of the thesis was provided.

Chapter 2

2 MECHATRONIC DESIGN CONCEPTS AND REVIEW

2.1 Introduction

This chapter examines the characteristics of global manufacturing and provides a comprehensive review of CIM, definitions and the evolution of mechatronic concepts as well as shopfloor control system architectures. The CIM cell that has been built at the University of KwaZulu-Natal with its individual constituent mechatronic components will be elaborated.

2.2 Global Manufacturing

Global competition in manufacturing and changing consumer demands have resulted in a trend towards greater product variety, innovation, shorter product life cycles, lower unit costs and higher product quality (Gunasekaran). As a consequence manufacturers are experiencing significant new demands and challenges to remain competitive. In particular, it is becoming strategically important for manufacturers to:

- Shorten the design to market lead-time. This results in the need to design "right-first-time" since there is not enough time to correct design errors or to re-engineer products for lower cost or higher quality.
- Ensure goods are produced to a high and consistent quality.
- Forecast production costs and lead-times in order to help assess the market potential of a product prior to significant investment.
- Alter production capacity in response to changing demands without incurring significant costs or production lead-times.
- Introduce new products frequently to retain or gain market share.

Manufacturing systems can be organised in many ways, the proper layout largely depends on the production volume and product variety; see Figure 2.1. At low volumes and high product variety, a job-shop layout is favourable, in which resources are grouped according to process type. As the volume rises, there are advantages to dedicating production resources to certain product families or even to specific products. At intermediate volumes and variety, resources therefore are often grouped into cells, each dedicated to certain product family. Shop-floor environments consisting of such cells are often referred to as flexible manufacturing systems.

Furthermore, at very high volumes and low product variety, there are advantages in arranging the resources according to the operation sequences, generally referred to as *flow-lines*, rather than grouping the resources according to process type. The focus of this research in on manufacturing systems organised in cells with medium production volumes and product variants.

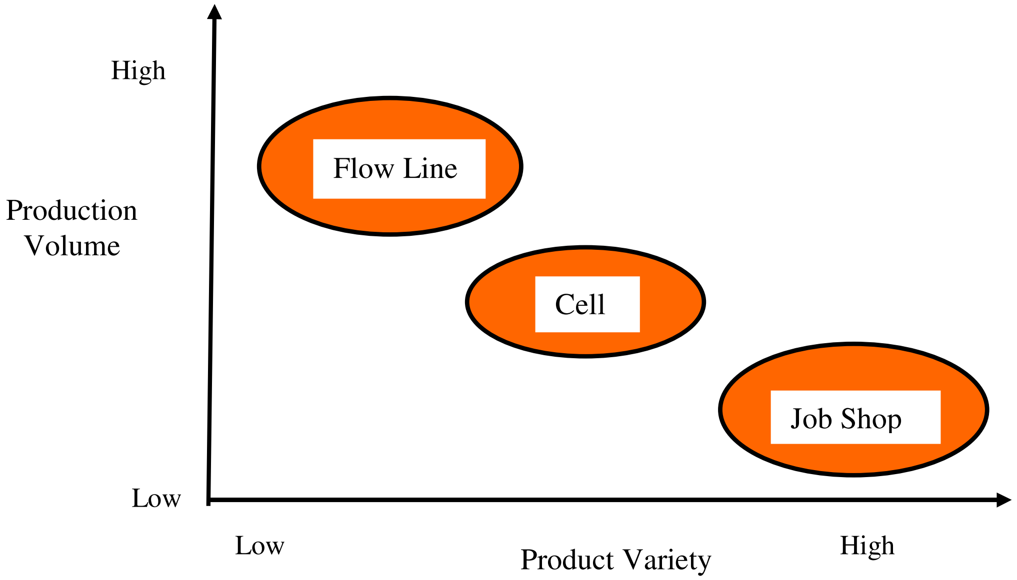


Figure 2.1 Manufacturing Systems Layout

2.3 Flexible Manufacturing Systems (FMS)

FMS is a general term used for a broad collection of manufacturing systems with varying forms. It is a highly automated machine cell, comprising a group of processing workstations, usually computer numerical controlled (CNC) machine tools, interconnected by an automated material handling and storage system, and controlled by a distributed computer system (Groover). The FMS is capable of processing a variety of different part styles simultaneously at the various workstations, and the mix part styles and quantities of production can be adjusted in response to changing demand patterns. The FMS is most suited for the mid-variety, mid-volume production range. Types of FMS could take a format as below;

(a) A single flexible machine (SFM) is a computer-controlled production unit which consists of a single CNC machine with tool changing capability, a parts storage buffer, and if necessary also a material-handling device.

(b) A flexible manufacturing cell (FMC) is a type of FMS consisting of a group of SFMs sharing one material-handling device.

(c) Flexible manufacturing system (FMS) consists of 4 or more workstations connected by common part handling system and distributed computer system. Other stations may support the activities, such as a coordinate measuring machine (CMM) or washing station.

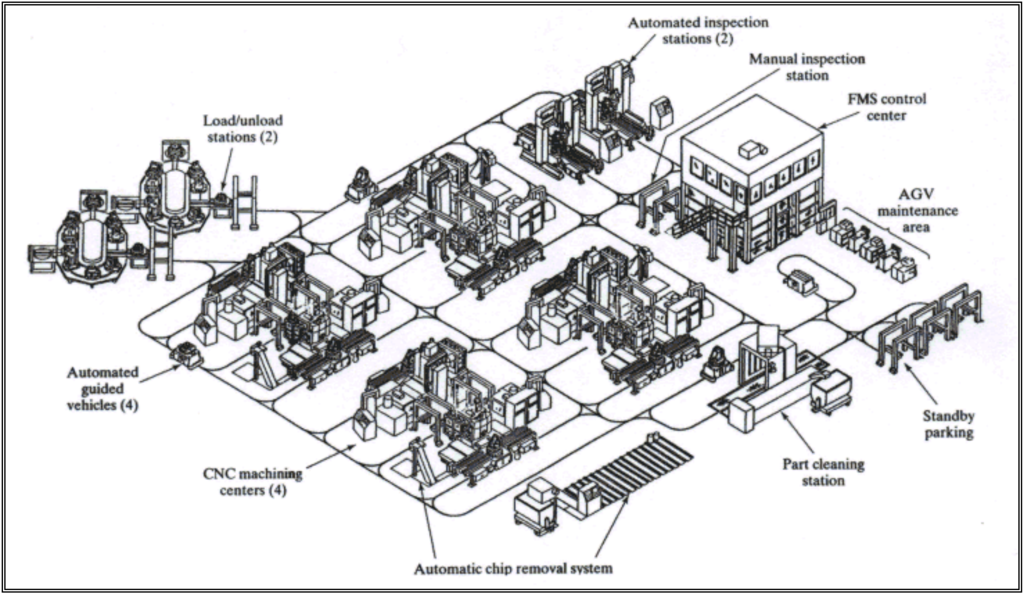


Figure 2.2 Flexible Manufacturing System Layout (Groover)

2.3.1 Manufacturing Resources

Despite the range of definitions of FMS and related terms, there is better on the agreement on the types of basic resources generally found in an FMS. Usually the resources are classified according to their processing capabilities namely:

- Material Processors (MP) are those resources that can process parts autonomously, e.g. machining centres, assembly machines, and inspection devices.
- Material Handling (MH) and storage systems are buffer stores and material handling devices.
- Material Transporters (MT) are responsible for moving parts throughout the factory, e.g. AGVs, conveyors, and fork trucks.
- Computer Systems (CS) coordinates the activities of the FMS components to achieve smooth overall operation of the system.

2.4 Computer Integrated Manufacturing (CIM)

The main objective of manufacturing automation is to utilize automated mechanical, electronic and computer-based systems in operations to increase the productivity of manufacturing systems. Extensive research has been going on in this field for many years, and these systems have now been implemented in the manufacturing industry all over the world. Other than the elimination of costly direct labour, the most compelling side of manufacturing automation is its ability to relax the limitations imposed on the manufacturing systems by human involvement. Machine operators are subject to certain physical and mental constraints which necessitate the systems surrounding them to have special designations satisfying these conditions. Limitations of human ability substantially restrict the throughput of the systems and lower the quality of the products. Today, highly competitive market conditions make companies prefer manufacturing automation wherever possible to maximize product quality and production efficiency (Hannam).

Modern industrial companies face an increasing need to adopt changes to meet the demands of the customers in the competitive environment. CIM is seen as a key competition strategy for industries in the twenty-first century. CIM uses a combination of systems and technologies designed to integrate the data and information of a company's business, engineering, manufacturing, and management functions. CIM has been defined as an integrated system of manufacturing, business and other engineering functions through the use of a set of computers (Hannan). All of the engineering functions in CIM, including design engineering, process planning engineering, and production engineering, play a crucial role in achieving the integration requirements between functions. Ranky describes the CIM concept in a similar way as the integration of four areas (Figure 2.3):

- Business Information System (BIS), that embraces all factory level planning and control activities, e.g. production planning, inventory control, purchasing, etc,
- Computer Aided Design, (CAD), this incorporates computer based tools to model and design products.
- Computer Aided Manufacturing, (CAM), incorporating also computer-aided-process-planning, (CAPP).
- Shop-floor Control Systems, (SFCS), covering both manual control automatic systems, e.g. flexible manufacturing systems (FMS).

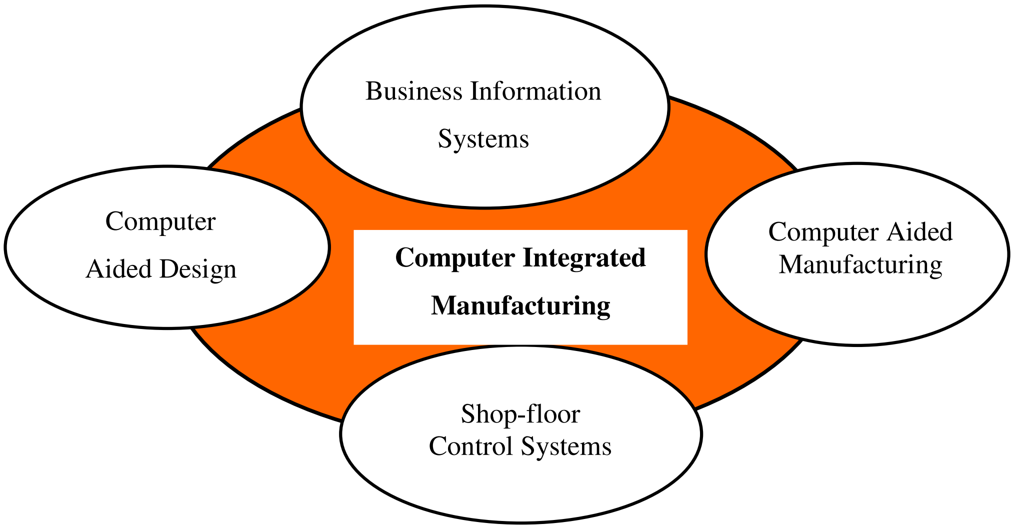


Figure 2.3 Computer Integrated Manufacturing System (Ranky)

CIM utilises concepts such as MSS and other associated technologies to integrate the data and information of a company's business, engineering and management function. The old divisions between electronic and mechanical engineering have been replaced by the integrated and interdisciplinary approach to engineering design referred to as mechatronics. In this highly competitive environment, the success of manufacturing industries in and selling their goods to the world market increasingly depends upon their ability to utilise mechatronic concepts into a wide range of products and processes.

2.5 Overview of Mechatronics

Today, cost-effective electronics, microcomputers, and digital signal processors have brought technology to appliances as well as consumer products. Systems utilising precise sensors and actuators have increased the performance of products tremendously. There are many designs where electronics and control systems are combined with mechanical components, but with little synergy and poor integration. This design becomes just a marginally useful, error-prone, expensive conglomeration. Mechatronic design concepts encapsulate synergism and integration which is different from just a traditional, multidisciplinary system.

The portmanteau "Mechatronics" was first coined by Mr. Tetsuro Mori, a senior engineer of the Japanese company Yaskawa, in 1969 as a combination of "mecha" of mechanisms and "tronics" of electronics and the company was granted the trademark rights on the word in 1971 to describe the philosophy in design of electro mechanical products to achieve optimum systems performance [Harashima, F. and Tomizuka, M]. There are numerous definitions by many researchers, practitioners and educators in the field of mechatronics; however none of them can always be complete in describing mechatronics, since the field is continually evolving [Bradley].

In the late 1980s and early 1990s, a number of attempts were made to provide a definition of mechatronics including that of the EEC Technical Committee on Mechatronics which read: *"Mechatronics is the synergetic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and processe*s." An alternative definition took the form: *"Mechatronics represents an approach to the design of engineering systems which involves the integration of mechanical engineering, electrical and electronic engineering with software engineering and computer technology at all levels of the design proces*s" see Figure 2.4 [Craig].

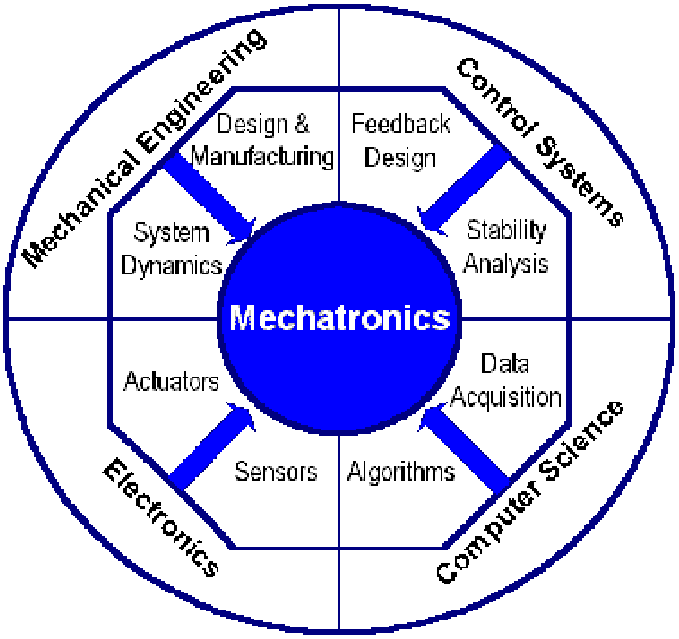


Figure 2.4 Mechatronics: Synergism and Integration through Design [Craig]

The objective of mechatronics is to design better products and production systems by making optimal use of the possibilities of mechanics, electronics and software, see Figure 2.5. This approach is not new, in fact, many companies have already been implementing mechatronic concepts for many years. However, the awareness of mechatronics as a competitive edge in the design of products and production systems has been growing over the number of years.

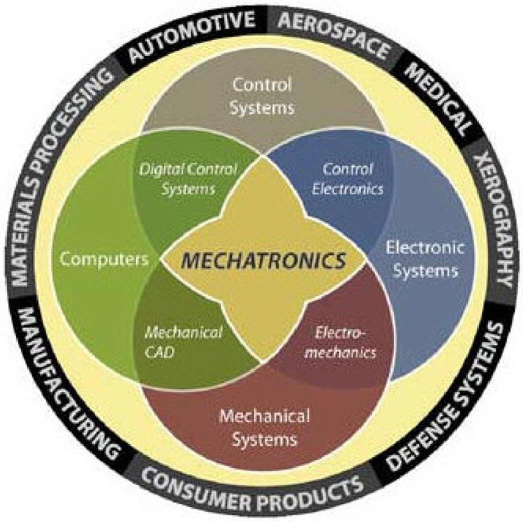


Figure 2.5 Features of Mechatronic Concepts (Craig)

Following the changing market situation that resulted in increased diversity of products, there is growing demand to rapidly re-configure production systems. The system must be flexible enough to handle a range of product types with short production runs without changeovers that require significant amounts of time. Well known examples of mechatronics systems (including robots, AGVs, and CNC machine tools) play a significant role in the concept of flexible production systems. Another area in which mechatronics has been fully adopted and has demonstrated its added value is in the development of production systems for electronic components and printed circuit boards (Fukuda and Amakawa).

Besides the development of production systems, the mechatronic approach has led to a revolution of consumer products such as:

- The improvement of existing products by offering more functions (features), higher reliability, and cost reductions;

- The development of completely new products, which would not have existed without the full integration of mechanics, electronics, and software (for example video cameras and compact disc players etc.).

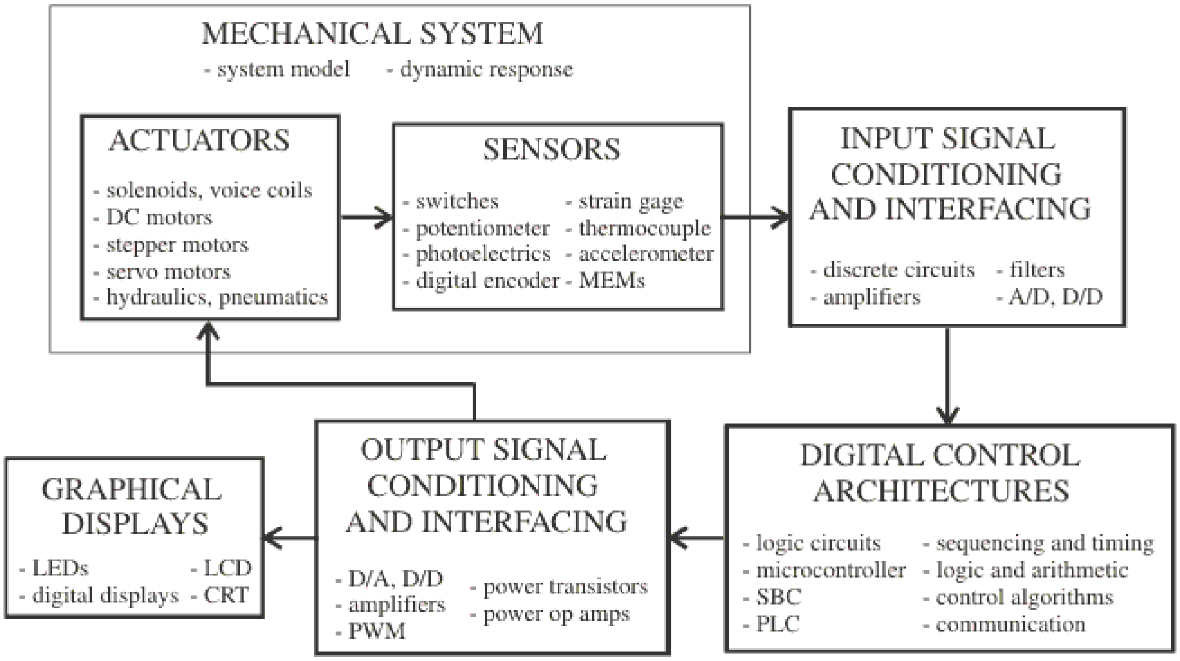


Figure 2.6 Components of a Mechatronic Systems [Alciatore and Histand]

Figure 2.6 illustrates all the components of a typical mechatronic system [Alciatore and Histand]. This system comprises:

- The actuators that produces motion or cause some action;
- The sensors that detect the state of the parameters, inputs, outputs, digital devices and control systems;
- Conditioning and interfacing circuits that provides connection between the control circuits, the input and output devices and,
- The graphical display that provides the visual feedback to the users.

2.5.1 Characteristics of a Mechatronic System

In comparison to classical products, mechatronic products can be characterised through the features illustrated in Figure 2.6 which comprise:

- Mechatronic systems being distinguished from classical systems by a greater number of sub-functions (complexity), that can be realised on a different physical levels which are supported by many different technologies during manufacturing (heterogeneity);

- The functions of mechatronic systems is based on the interaction of heterogeneous sub-systems and crucially effected by the automatic control;

- The utilisation of the opportunities given by the automatic control for the implementation of required system features allows to extend the area of operation significantly and to adapt it flexibly to special requirements (tuning, adaptation, and learning). In the interest of novel system features, the main functions are complemented by structurally embedded support functions;

- The complexity requires the application of methods of function and configuration oriented system analysis like partitioning, hierarchical, modular structuring, and integration.

2.5.2 Evolution of Mechatronics

Historically, mechatronics grew out of the use of computer based technologies to provide increased levels of performance from mechanical systems in the area of machine tools and subsequently covered a wide range of engineering systems and products. This came from the realisation, largely by mechanical engineers, that development in electronics and software could support significant performance enhancements in purely mechanical or existing electromechanical systems. Electronics and software meanwhile continued along their own, separate, development paths and today the mechatronics base remains substantially within the mechanical engineering community [Bradley].

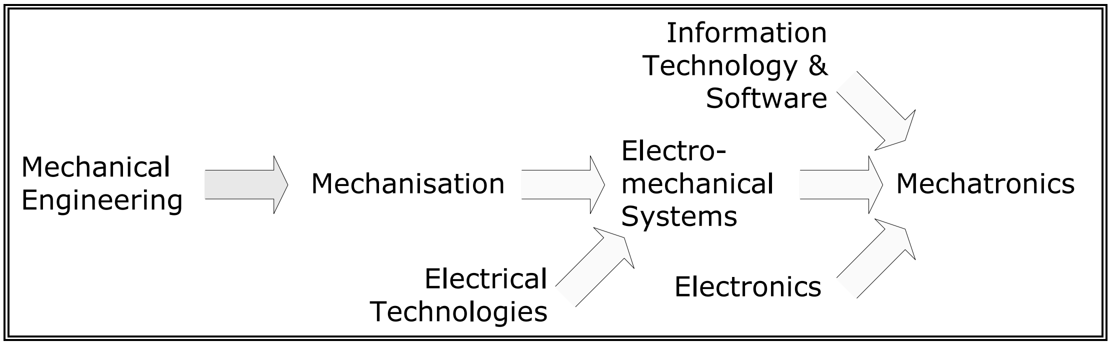


Figure 2.7 Evolution of Mechatronics [Bradley].

The evolution of mechatronics has gone through three stages (Bishop). The first stage corresponds to the 1970's around the introduction of the word. During this stage, technologies used in mechatronics systems developed rather independently of each other and individually. Mechatronics was concerned mostly with servo technology used in products such as automatic door openers, vending machines, and autofocus cameras. Simple in implementation, the approach encompassed the early use of advanced control methods.

The second stage took place in the 1980s with a synergistic integration of different technologies, the notable example being in optoelectronics (i.e., an integration of optics and electronics). The concept of hardware/software co-design also started in these years. As information technology was introduced, engineers began to embed microprocessors in mechanical systems to improve their performance. Numerically controlled machines and robots became more compact, while automotive applications such as electronic engine controls and antilock-braking systems became widespread.

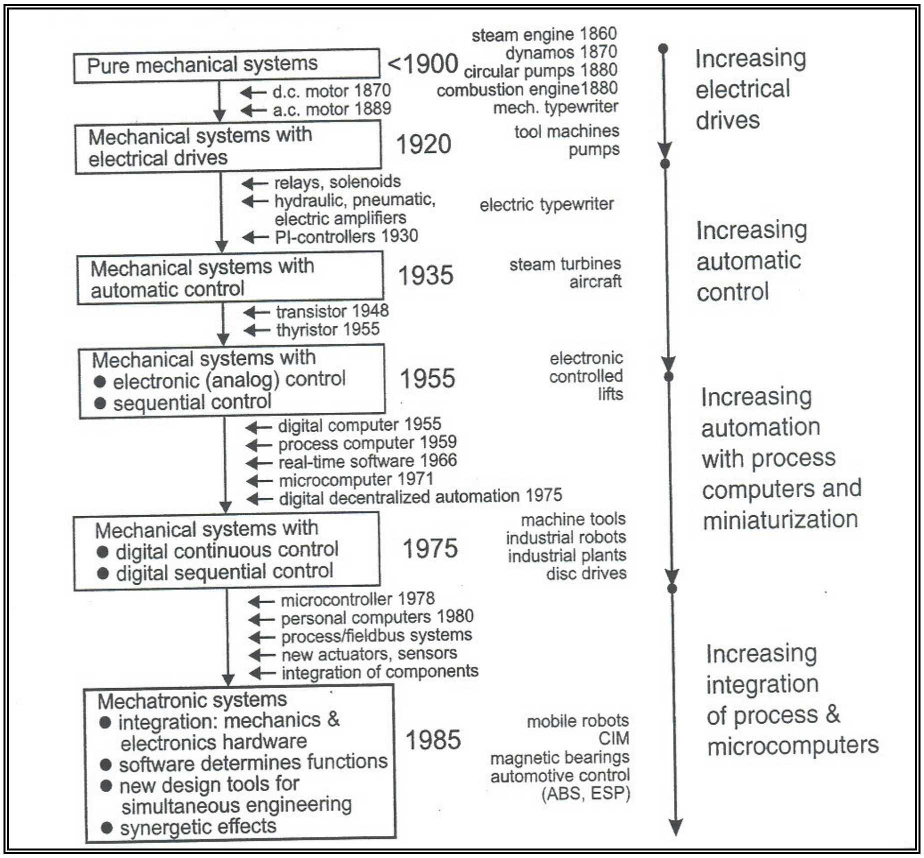


Figure 2.8 Historical Development of Mechatronic Systems [Bishop]

The third stage, in the 1990s, can be considered as the start of the mechatronics age. The most notable aspect of the third stage is the increased use of computational intelligence in mechatronic products and systems. It is due to these developments that aspects such as Machine Intelligence Quotient (MIQ) became prevalent in the industrial settings. Communications technology was also added to the mix, yielding products that could be connected in large networks. This development made functions such as the remote operation of robotic manipulator arms possible. At the same time, new, smaller--even micro scale sensor and actuator technologies (i.e., micro mechatronics) are being used increasingly in new products. Microelectromechanical systems (MEMS), such as the tiny silicon accelerometers that trigger automotive air bags, are examples of the latter use.

2.5.3 The Team Approach Concept

The team approach is an important pre-requisite for the effective development of state-of-the-art mechatronics systems. Teams of specialists from different disciplines have to pool their knowledge to design high quality products. No single designer can have all the knowledge needed to design mechatronic products and there are also no computer-based design tools available to replace the "team function". The quality of a mechatronic concept depends on the skills of the representatives of the disciplines and in particular their ability to co-operate. Members are generally individuals separated by disciplines and/or functional responsibility – thus communication can be difficult due to lack of "share meaning" as shown in Figure 2.9 (Konda et al.,).

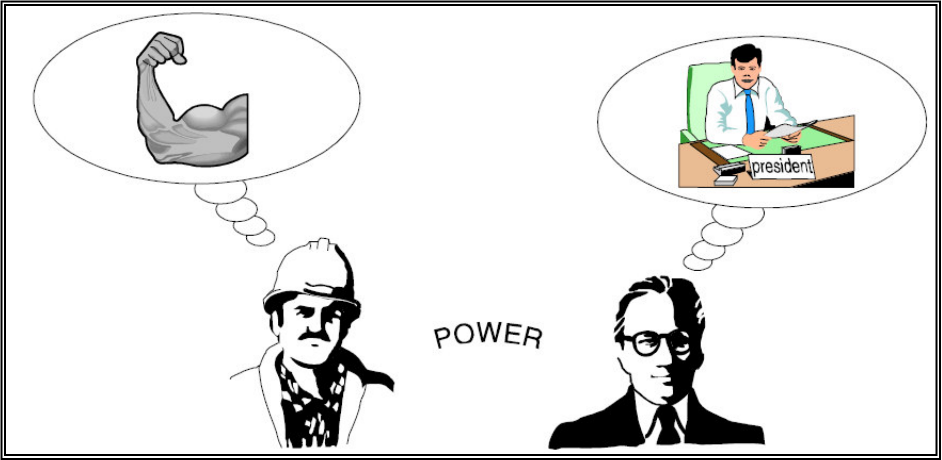


Figure 2.9 The concept of "Lack of Shared Meaning"

Figure 2.10 The MR^{2}G Laboratory CIM Cell Layout

2.6 University of KwaZulu-Natal CIM Cell

Figure 2.10 shows an oerview of the components that comprises the University of KwaZulu-Natal CIM cell at the Mechatronics and Robotics Research Group (MR^{2}G) laboratory. Raw materials, work-in-process and finished goods are stored in the single aisle vertical automated storage and retrieval system (AS/RS). The parts are transported among the different workstations using a conveyor belt, a PC based PUMA robot and indexing devices for the AS/RS. An automated guided vehicle (AGV) is also used for parts delivery operating in an omni-directional manner. This system allows the AGV to be integrated with a conveyor system such that there will be a physical mating between the AGV and part conveyor. This results in the reduction of part handling time and docking space between the AGV and the conveyor. Components are processed by MAHO MH 400C Milling machine with a CNC Heidenhain controller. A Co-ordinate Measuring Machine (CMM) station adds flexible quality control to the cell by reducing the need for fixturing and special gauges during inspection.

As the CMM is computer controlled, inspection data can be stored and inspection programs can be executed automatically. The Automated Visual Inspection System (AVIS) is an automated visual inspection system that is capable of monitoring the quality of a manufactured part throughout its manufacturing cycle. By placing an individual inspection apparatus at identifiable inspection nodes in the manufacturing process, AVIS can successfully achieve in-process verification. The individual inspection apparatus utilise specifically designed camera positioning and part manipulation systems to position digital cameras at known viewpoints within their inspection envelopes (Bright and Mayor, 1999). A detailed explanation of the CIM cell components will be covered in chapter 4.

2.7 Architecture of Shop Floor Control System (SFCS)

The SFCS receives product orders provided by the business system. The related process plans are provided by the process planning engineer, and the product models are provided by the production engineer. The product orders may contain due-date, quantity, priority and so on. The Manufacturing Systems Integration project (MSI) at the National Institute of Standards and Technology (NIST) has developed a system architecture which is composed of an integrating infrastructure and a set of modules, including process planning, production planning and scheduling, order entry, and control (Senehi *et al.*). The project addresses production management and control problems within a shop controller. The Real-time Control System (RCS) has been also suggested at NIST as reference model architecture for a wide variety of applications that require intelligent real time control (Albus *et al.*). The RCS has seven layers such as shop, cell, workstation, equipment, elemental-move, primitive, and servo. (See Figure 2.9) At each level, the controllers are partitioned into four generic modules: task decomposition, world modelling, sensory processing, and value judgment.

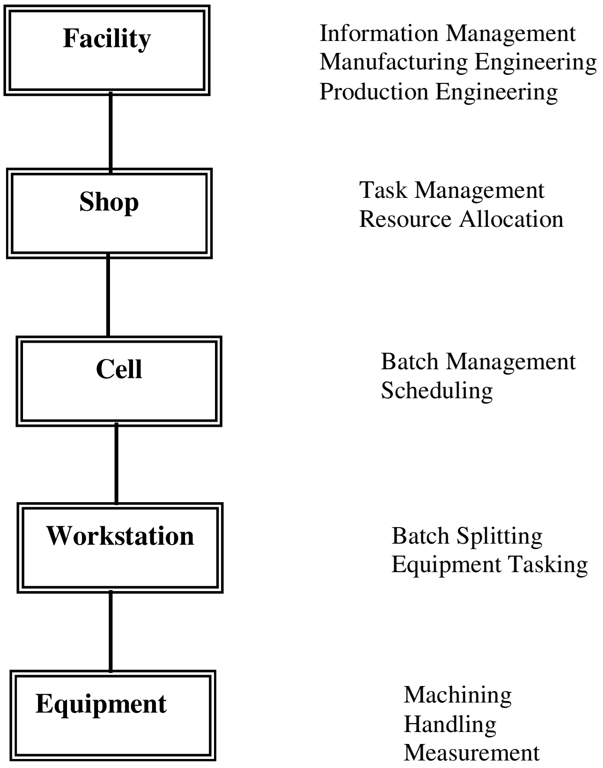


Figure 2.11 Hierarchical Shop floor Control System

Shop floor control for discrete part manufacturing has been widely described by many researchers, which have led to several frameworks to solve the overall shop floor control problem. These frameworks have been called control architectures, control structures, and control models, etc. [Chang et al., 1998].

Once each equipment controller is constructed, it is necessary to define the workstation control activities necessary to coordinate the functions of the shop floor. SFCS is decomposed into a series of smaller levels; each level consists of several functions determined by grouping events occurring at different frequencies. Each of the groups can be controlled by a function. The number of these functions, that is, different frequency groups, depends on the authors involved or the methodologies used. However, any intelligent controller must integrate a decision-making function (planning and scheduling) and an execution function (monitoring and error recovering) (Davis *et a*l.). Therefore, the controller at each level in the hierarchical control architecture must have the ability to read inputs and make decisions based on the inputs and current system status, and to generate outputs. In this research, three functions - planning, scheduling, and execution - are adopted.

Decision-making functions correspond to the planning and scheduling functions, while message reading and generation functions correspond to the execution function. Table 1.1 summarizes the functionality.

Level Functions	**Equipment**	**Workstation**	**Equipment**
Planning	• Tool Selection and tool path refinement • Tool assignment to slots, job set-up planning	• Resource Allocations • Batch splitting • Equipment load balancing	• Batching • Workload balancing between workstations • Task allocation to workstations
Scheduling	• Operation sequencing at individual equipment	• Sequencing equipment level subsystems • Buffer management • Deadlock resolution	• Assignment of due dates to workstations • Batch sequencing and management
Execution	• Interface to workstation controller • Physical control of machines • Execution of control	• Monitor Equipment states and execute part and information based on states • Synchronisation	• Organisational control of workstations • Interface with MRP • Report generation

Table 1.1 Functional Architecture of a Shop Floor Control System

The planning function at each level receives a series of job orders and related process plans from the upper level controller and prepares a set of tasks to be scheduled. Specifically, the planning functions of the shop and workstation controllers manage batches, determine part routing, and allocate resources (e.g., material handler, tool, and fixture, attendant). The planning function of the equipment controller determines operation routing (e.g., tool path) and performs machining parameter optimisation. The scheduling function at each level is responsible for sequencing and dispatching the multiple batches/parts in order to resolve resource contention. The scheduling function also helps the system maintain in a deadlock-free state. Scheduling decisions for shop floor control are usually made in real-time on the basis of single-pass scheduling rules or multi-pass scheduling techniques.

The execution function at each level interprets incoming messages, detects and corrects error situations, and broadcasts newly created messages to other controllers. It also coordinates the planning and scheduling functions. In particular, the execution function of the equipment controller monitors device status, downloads CNC instructions and robot programs to the control unit, and performs synchronization activities in transferring parts between two pieces of equipment.

2.8 Enabling Technologies for Decision-Making Functions

The operation management function in each controller optimises various operations to finish the assigned tasks within the due date. For CNC machines, it is responsible for generating CNC codes. As the process plan graphs in AND/OR graph formats are obtained from the Computer Aided Production Planning (CAPP) system, the function selects the set of features to be machined and determines the sequence of features in the selected set. Serialising the process plan graph can be modelled as a revised travelling salesman problem and solved by the neural network method. However, it is difficult to apply the model to real-time control since the required computing time is high due to the repeated computations needed for convergence. Although a grouping and sequencing methodology for managing an assembly plan graph have been proposed, its purposes and contexts are not appropriate for real-time shop floor control (Cho).

2.9 Chapter Summary

In this chapter, an examination on the characteristics of global manufacturing was done. This led to a comprehensive review of CIM, definitions and the evolution of mechatronic concepts as well as shopfloor control system architectures. The CIM cell that has been built at the University of KwaZulu-Natal with its individual constituent mechatronic components was elaborated.

Chapter 3

3 THE DESIGN OF MECHATRONIC SENSORY SYSTEM

3.1 Introduction

This chapter details the design of the mechatronic sensory system, highlighting conceptual development thereof. Several design concepts are presented and discussed as an illustration of the evolution of the final MSS apparatus. The remaining sections of the chapter provide a detailed analysis of the conveyor motion system and the frames in which the sensors are mounted.

3.2 Mechatronic Design

A modular design approach was implemented in designing the mechanical conveyor structures, mechatronic sensory feedback and control of the proposed system. The initial step in was to design the conveyor system and the mechatronic sensors in the indexable conveyor system. There was also the design of the scanner structure system to utilise the scanner and bar coding system to determine characteristics of the material billets.

The sensory feedback capability of the system was integrated in order to monitor the processes, positions and to take the necessary control actions within the system. Thus, an in-depth knowledge of sensors, signal acquisition and conditioning was necessary as well as interfacing technology during the design of the MSS apparatus.

The control of different mechatronic actuation of the proposed system was to be implemented using suitable motors. The power electronics, which comprised the motors and the control circuitry had to be built in order to control the components at the desired time, speed, direction, and with some desired accuracy. The software control and the platform on which the software was running for the apparatus had to be implemented on the PC in order to control the motion of the apparatus smoothly in accordance with the sensory feedback information and the operator commands.

From the above discussion, it can be seen that the technology used to develop the proposed system was a synergy of mechanical, electronic/electrical, information technology and control engineering. The design principle of the developed system was thus a modular mechatronic design (ref. Figure 2.6).

3.3 Conceptual Design

This section presents the conceptual designs that led to the final design implemented in constructing the MSS apparatus and the scanner for the automated data collection. The overall design of the mechatronic sensory system was governed by the following prodct design specifications:

- The system had to facilitate the automated operation of the conveyor system, operate image acquisition of the pallets movements in the conveyors and had to be simple in operation;
- The material to be transported;
- The sensors to be used in the system;
- The developed system had to be easily integrated within the CIM cell.

3.3.1 The Material

In order to design the material handling system, it is important to know the type of material to be handled. The following are some of the properties to be considered:

- Weight
- Volume
- Shape
- Phase (i.e. solid, liquid or gas)
- Temperature
- Viscosity(if liquid)
- Corrosiveness
- Flammability

The material handling system had been specified as a hollow wooden pallet that could accommodate various components to be transported around the CIM cell.

The pallet was of the following dimensions:

Length:	200 mm
Width:	200 mm
Height:	45 mm

Figure 3.1 shows an illustration of the pallet with a cylindrical component.

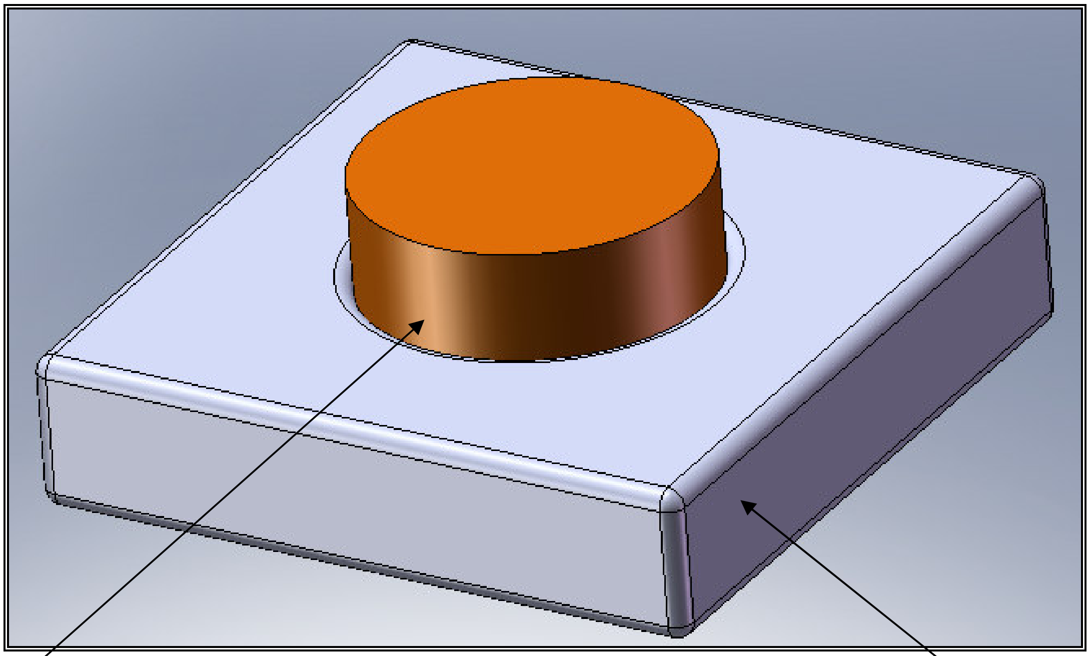


Figure 3.1 Illustration of the wooden pallet

These pallets would be at room temperature and weighed approximately 0.5 kilogram. However, for practical design purposes a 10-kilogram weight was assumed. The pallets were not toxic, corrosive or flammable but would burn at elevated temperatures. Due to the large surface area of the base, the pallets were well balanced and very stable when resting on their bases, a position in which they could safely support their own weights. This made for a favourable orientation in which the pallets should be transported. However, since the pallets were hollow, they could not be subjected to clamping forces in excess of 50 Newtons. Being of overall sturdy construction, the wooden pallets could be handled by a variety of material handling methods such as robots end effectors without any risk of incurring damage.

3.3.2 Conveyor System Design

Powered roller conveyor system was adopted in that the distances travelled by goods could be increased and the speed at which the pallet could be controlled by varying the motor speed. The roller elements were of tubular design encased roller bearings positioned at each end. The bearings were used to minimize friction and noise during conveyor system operation. The roller conveyor system comprised of rollers that are perpendicular to the direction of travel.

The conveyor system consisted of six different tracks combined to form the oval configuration as shown in Figure 3.2. The conveyor sub-system comprised of two straight sections and four sections consisting of 90^0 semi-circular sections (ref. Figure 3.3). Each conveyor section was driven by a 12V DC servo-motor and there were ten servo motors required to drive the initial and frictional loads in both directions in the conveyor system.

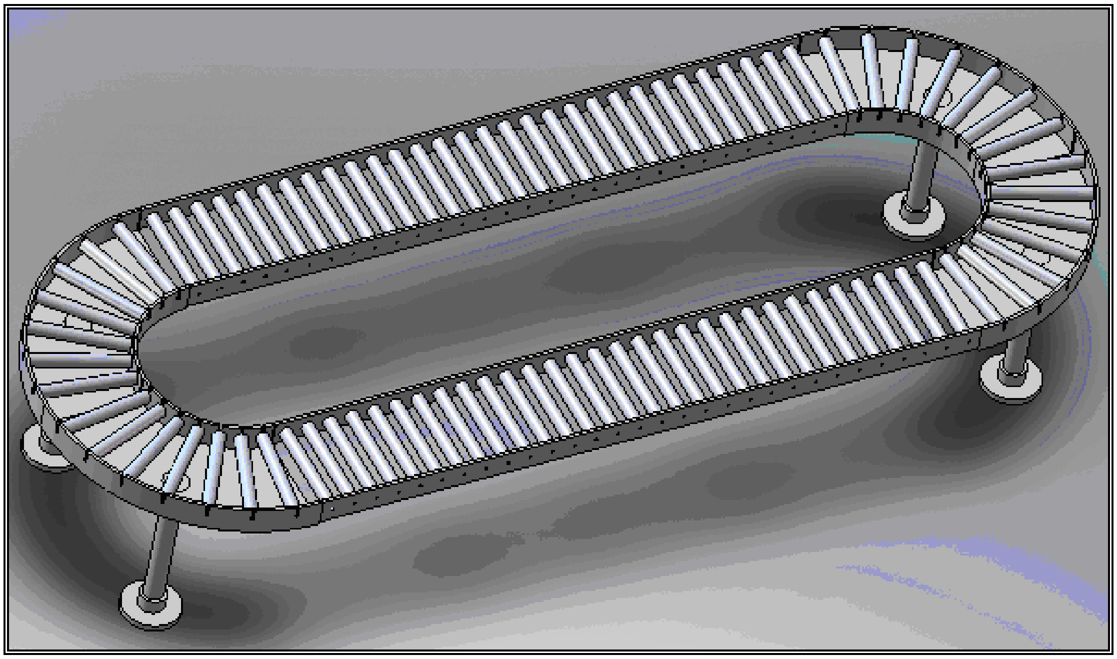


Figure 3.2 Complete Oval Modular Conveyor System

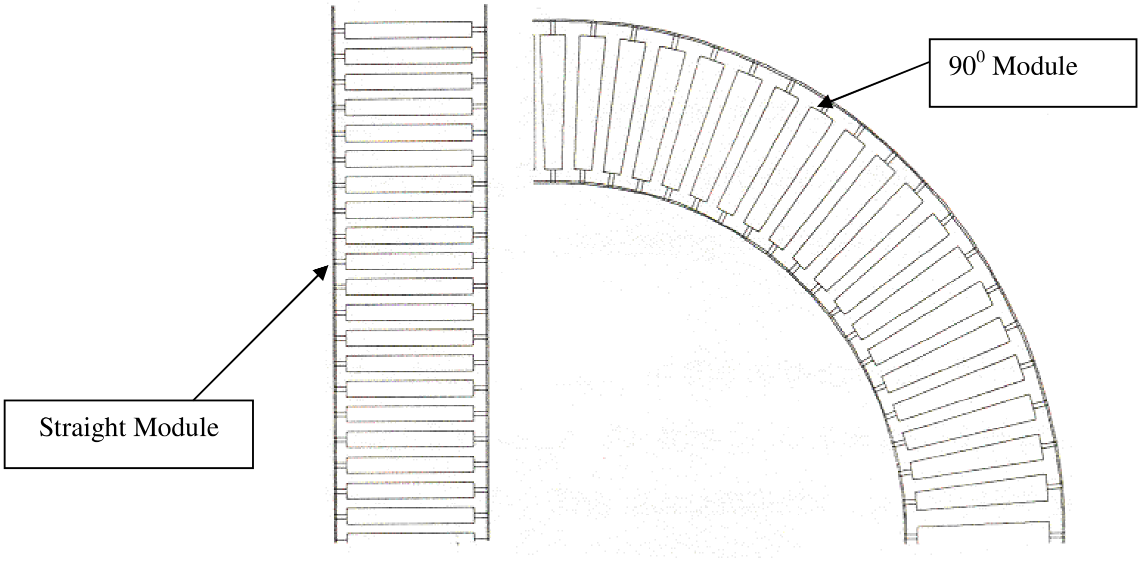


Figure 3.3 Different module configurations for conveyor system

The conveyor straight section consisted of two C-section channels of 1.6mm gauge sheet metal that were fixed parallel to each other and were approximately 300 mm apart. Thirty three rollers supported at either end by bearings were mounted between the two C-section channels. The rollers were perpendicularly mounted to the channels. The complete conveyor structure was supported by height adjustable legs being four in total (see Figure 3.5). Overall dimensions of the conveyor straight section were: LENGTH: 1.96 m

WIDTH: 0.375 m

HEIGHT (minimum): 0.54 m (maximum): 0.90 m

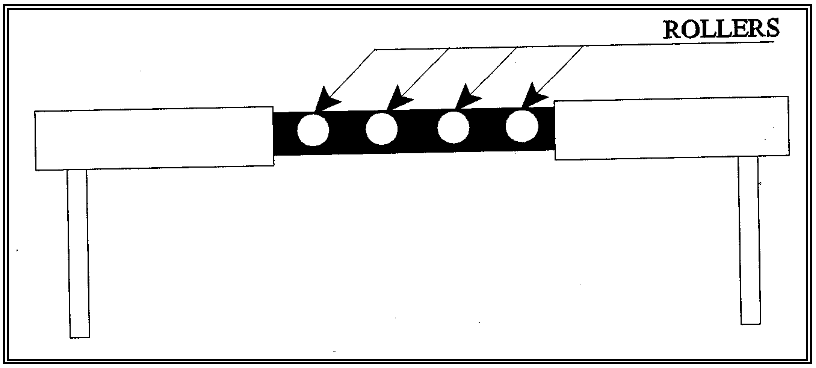


Figure 3.4 Side view of the conveyor

Figure 3.5 C-section channel after being sectioned off at mid-span

The AGV docking bay was created beneath the stationary conveyor to integrate the material transfer process. This required the conveyor's C-section channel be removed at the side where the AGV would enter see Figure 3.5. The rollers were mounted on the AGV with height adjustable characteristics to facilitate loading and off loading, see Figure 3.6 and Figure 3.7.

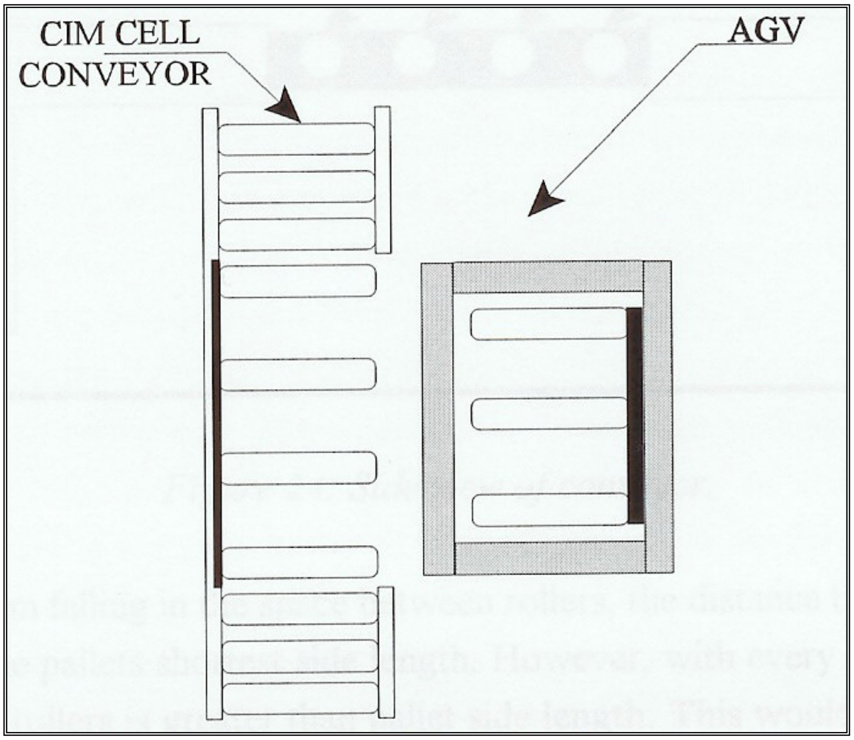


Figure 3.6 Plan view of Conveyor and AGV

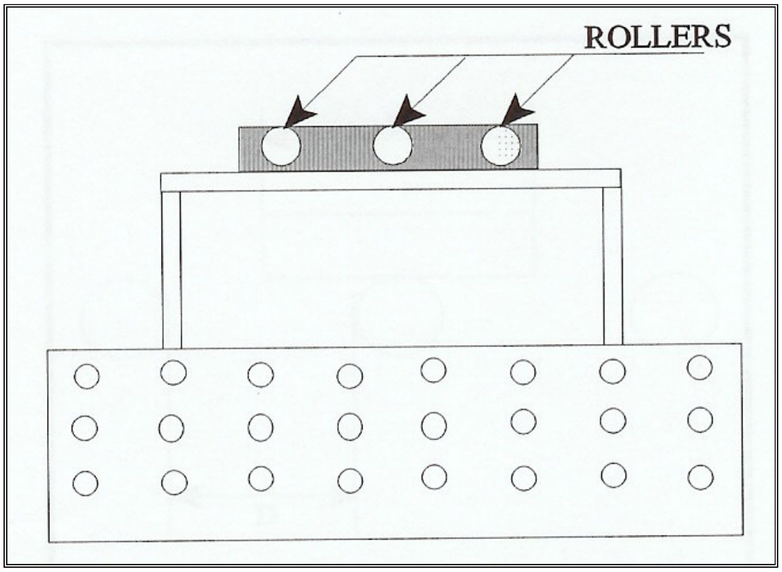


Figure 3.7 Rollers mounted on the AGV

3.3.3 Stress Analysis of Material Support Beams

The maximum weight to be supported by material support beams was ten kilograms (approximately 100 N). Stresses were be calculated using the unit load method since the beams were statically indeterminate. The statically indeterminate system could be analysed as a statically determinate system with redundant supports substituted by external loads. Once the values of these substituted loads were calculated, the overall bending moment diagram was obtained. Number of redundant support:

$$n = 3C - H \qquad 3.1$$

Where: C = number of closed contours in structure.

H = number of hinges including supports.

Therefore, n = 3.(1) - 0 = 3

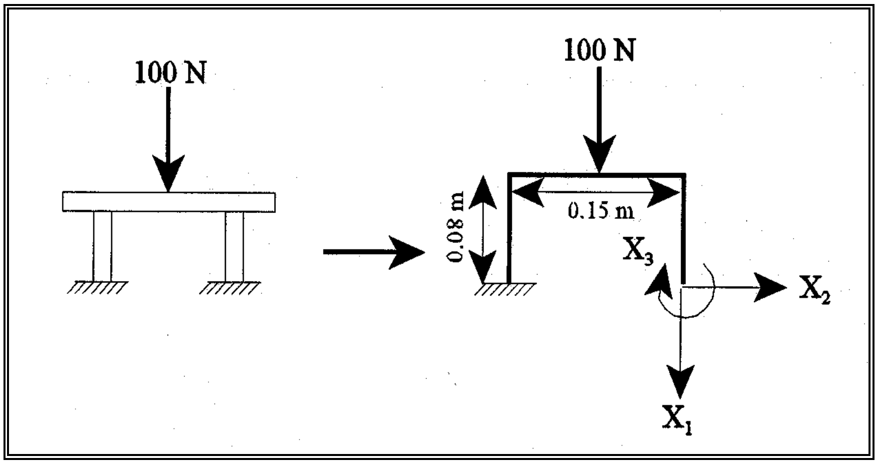


Figure 3.8 Stress Diagram

The bending moment diagrams M_1, M_2 and M_3 due to each of the units' loads X_1, X_2 and X_3 respectively are as follows:

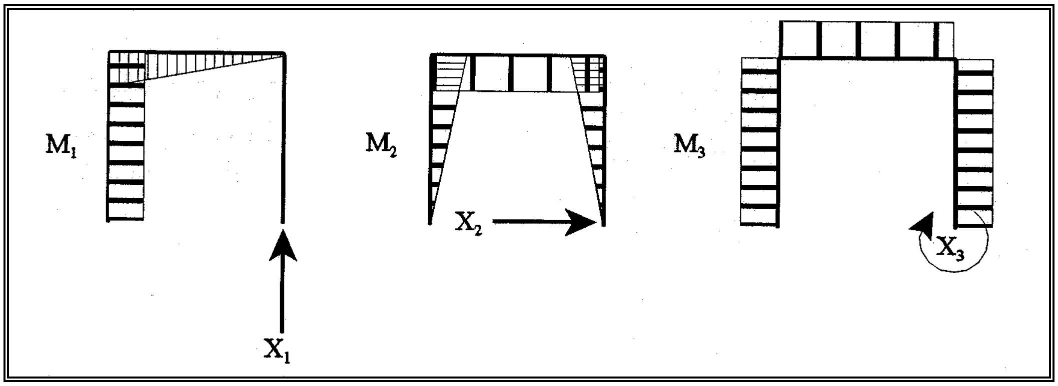


Figure 3.9 Bending Moment Diagrams

The bending moments that would be imposed on the statically determinate system by the loading conditions was as follows:

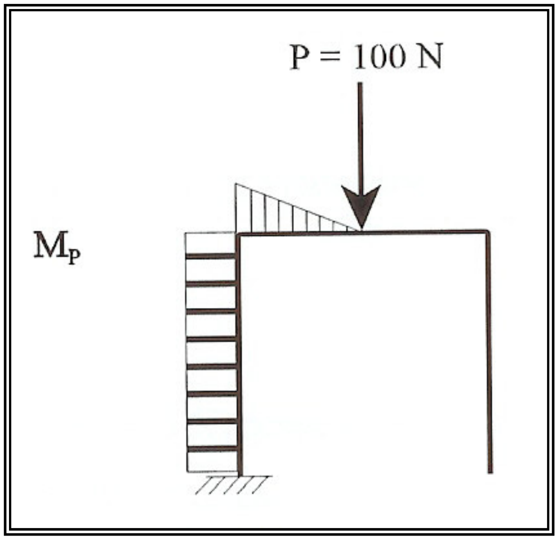


Figure 3.10 Bending Moment Diagram for the Statically Determinate System

Since there were 3 redundant supports, 3 equations in three unknowns, X_1, X_2 and X_3 needed to be solved:

$$\delta_{11} X_1 + \delta_{12} X_2 + \delta_{13} X_3 + \Delta_{1P} = 0 \qquad \ldots\ldots\ldots\ldots\ldots.. \quad 3.2$$

$$\delta_{21} X_1 + \delta_{22} X_2 + \delta_{23} X_3 + \Delta_{1P} = 0 \qquad \ldots\ldots\ldots\ldots\ldots.. \quad 3.3$$

$$\delta_{31} X_1 + \delta_{32} X_2 + \delta_{33} X_3 + \Delta_{1P} = 0 \qquad \ldots\ldots\ldots\ldots\ldots.. \quad 3.4$$

Using the formula $\delta_{ij} = L / 6EI\,(M_b.\,M_b' + 4\,M_c.\,M_c' + M_e.\,M_e')$ …….. 3.5
and solving for $\delta_{11}, \delta_{12}, \delta_{13}, \delta_{21}, \delta_{22}, \delta_{23}, \delta_{31}, \delta_{32}, \delta_{33}$ yielded:

$\delta_{11} = [16.686 \times 10^{-3}] / \mathrm{El}$
$\delta_{12} = [1.802 \times 10^{-3}] / \mathrm{El}$
$\delta_{13} = [-29.57 \times 10^{-3}] / \mathrm{El}$
$\delta_{21} = [1.802 \times 10^{-3}] / \mathrm{El}$
$\delta_{22} = [533.87 \times 10^{-3}] / \mathrm{El}$
$\delta_{23} = [-147.2 \times 10^{-3}] / \mathrm{El}$
$\delta_{31} = [-29.57 \times 1\,0^{-3}] / \mathrm{EI}$
$\delta_{32} = [-147.2 \times 10^{-3}] / \mathrm{EI}$
$\delta_{33} = [0{,}001\ 16 \times 10^{-3}] / \mathrm{El}$

Power roller conveyor systems was driven by electric motors with belts interlinking the drive mechanism, where power was transmitted from a belt, to a roller, and back to another belt (see Figure 3.11. This interlinking carried on along the whole length of the conveyor section.

Figure 3.11 Interlocking of conveyor belts

3.3.4 Choice of sensors for the Conveyor System

The choice of sensors for the conveyor system was considered. The modular conveyor segments required sensors so that the exact position of the pallet could be determined at various points along the conveyor. This data was needed to update the animation of the pallet movement for the user and by the host computer to establish the exact position of the pallet so that it can switch on or off the necessary conveyor segments allowing the pallet to reach its required destination. Sensors were also required for stopping the pallet at predetermined locations for loading and unloading by the Puma Robot. The system was to be able to accommodate pallet sizes of 200 mm x 200 mm and 250 mm x 250 mm. A number of optical, tactile and proximity sensors and other sensor designs were considered for applications for operation of the conveyor system. To choose the optimum sensor designs to be utilised in the MSS apparatus, the following considerations has to be taken into account:

(i) **Range:** The range of sensors, using time of flight measurement, based on opto-electronic technology was comparable but could extend to very close ranges.

(ii) Accuracy: Within the usage range, the sensors were to be capable of accurately achieving the desired results within 1- 2 mm. In the direct of flight (DOF) measurements, the error was to be approximately uniform over the full range, with rapid deterioration when the signal to noise ratio dropping below a certain threshold.

(iii) Cost: For commercial purposes, the costs of the sensors needed to be considered.

(iv) Specific environmental considerations: Opto-electronic sensors fail in the dark, matt environments whereas sonar fails in acoustically dead environments and thus consideration needed to be accounted on the choice of sensor type whilst being cognisant of the operating environment.

(v) **Size of sensors:**The beam width depended on the size of the focusing antenna relative to the wavelength.

3.3.4.1 Chosen Sensors

Tactile sensing requires a group of sensors arranged in a rectangular or square pattern called an array. The array has a number of sensing elements, each capable of measuring the continuously variable applied force to the element. A tactile sensor interfaced to an intelligent controller can determine the shape, texture, position, orientation, deformation, mass centre, and presence of torque and slippage of any object held. Tactile sensors are more useful in the applications where force or pressure can be developed between two surfaces being in close proximity to one another and there were found not ideal for use in the conveyor system.

Most sensors, however, proved to be too expensive or not readily available in the market. Optical sensors and limit switches seemed to be the most cost effective and practical since a large number would not be required and a simple Boolean output would be achievable without elaborate signal conditioning. Photodiodes and phototransistors were finally chosen over limit switches as they didn’t affect the path of the path of the pallet, would allow for differing pallet sizes and were not affected by “switch-bounce”.

3.3.5 Configuration of Sensors within the Conveyor

Conveyor system sensor configurations were considered with maximum flexibility of the system in mind.

3.3.5.1 First Conceptual Design of the Sensor Configuration

The first conceptual design involved sticking a strip of alternating reflective/non reflective tape (a “Zebra Strip”) to the bottom of the pallet (see Figure 3.11) and a co-axial light emitter/detector to the bottom, between the rollers at the ends of the conveyor segments (see Figure 3.13)

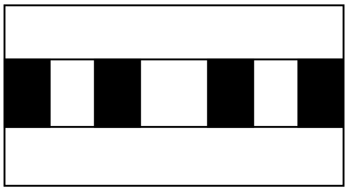


Figure 3.12 Bottom of Pallet with a Zebra Strip

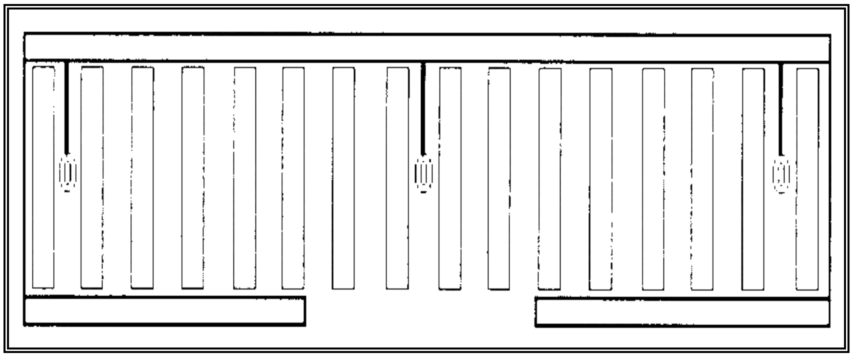


Figure 3.13 Conveyor fitted with sensors

When the pallet was not present, the light detector resistor (LDR)) was set up so that it was in a low state i.e. no light from the emitter is reflected off anything. This was achieved by either calibrating the LDR or using a pair of photoelectric transducers that respond to frequencies other than visible light. As the pallet passes by, the zebra strip caused the signal from the LDR to toggle between high and low. The software was then set up on a count for the toggle and used it to position the pallet and update the animation.

3.3.5.2 Second Conceptual Design of the Sensor Configuration

The second method utilised the light-emitter LDR pairs that are positioned at the ends of conveyor segments and at points requiring exact positioning. At the extreme ends of the conveyor, two sensor pairs are placed such that a 200 mm pallet would just block off both light beams (see Figure 3.14 [a])

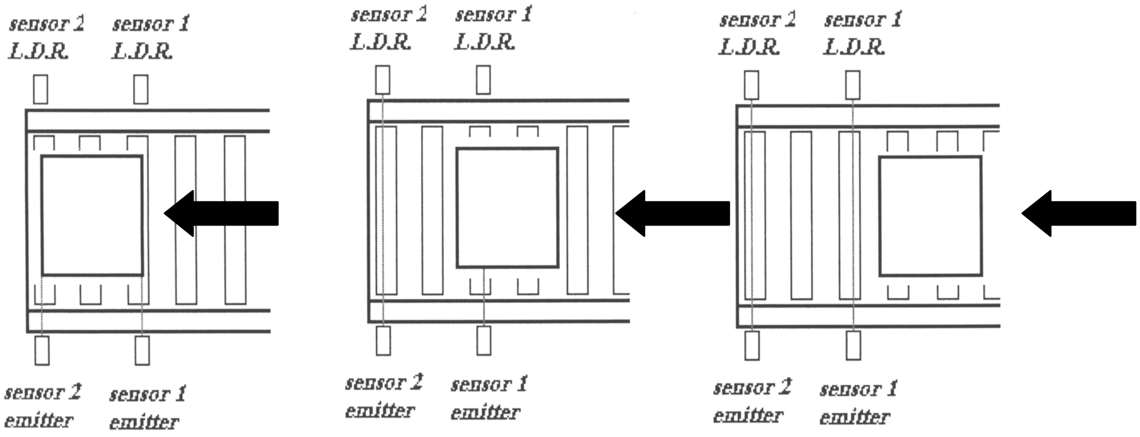


Figure 3.14 [a] Both Sensors register a pallet

Figure 3.14 [b] Sensor 1 register a pallet

Figure 3.14 [c] Pallet approaching from the right

Figures 3.14 [a, b, & c], Shows position of the pallet approaching from the right

SENSOR 1	SENSOR 2	STATUS
1	1	• No pallet
0	1	• Pallet approaching from right
1	0	• Pallet approaching from left
0	0	• Pallet position fixed • Update animation • Start/Stop next/previous conveyor segment depending on previous condition • Stop conveyor for Puma robot unload

Truth table 3.1

3.3.5.3 Third Conceptual Design of the Sensor Configuration

An array of sensors was considered in which the light curtain was generated by two light arrays, one containing a row of emitters and the other corresponding to a row of receiver phototransistors (Figure 3.15).

In this multiplexing arrangement, an electronic circuit control circuit interrogated each sensor in the array in sequence. However this concept was found to be expensive taking into account the number of emitter-receiver sensor pairs to be used.

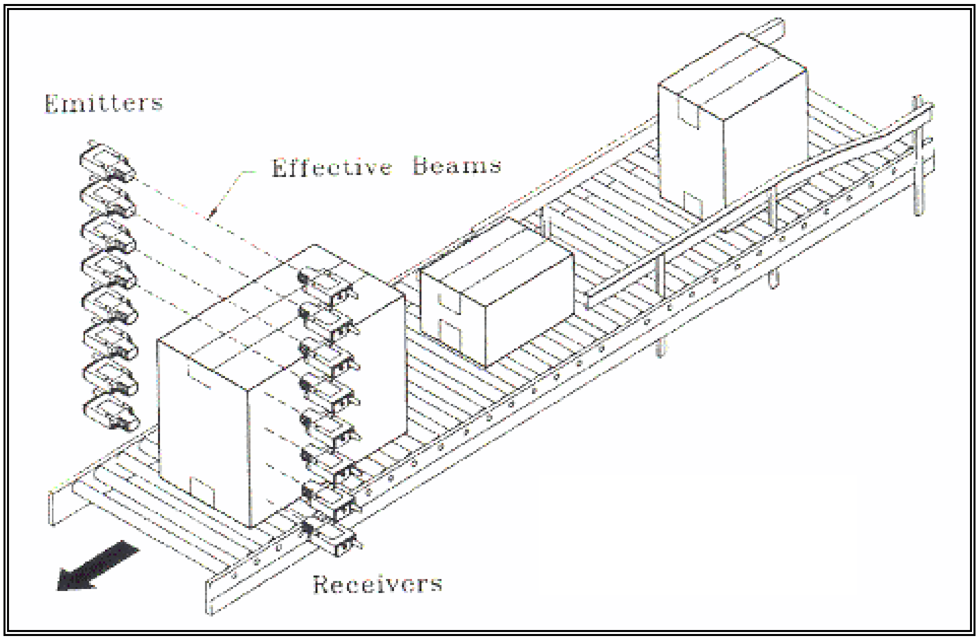


Figure 3.15 An array of multiplexed sensors

Although the second concept used almost twice the number of sensors compared to the other concepts, it was found to be the most robust solution. The main disadvantages of the first concept is that production places, such as CIM cell, are usually dirty environments and a dirty zebra strip could provide erroneous information. The other problem is that accidental reflections by CIM cell equipment say a PUMA robot moving overhead, could give false signals.

3.4 Chapter Summary

In this chapter a design of the mechatronic sensory system apparatus has been proposed, highlighting conceptual development thereof. This method models real-time data acquisition and visualisation of the MSS apparatus. Several design concepts were presented and discussed as an illustration of the evolution of the final MSS apparatus. Utilizing morphological matrices, a conveyor was chosen as the optimal material removal concept and light emitting-receiver pair sensors were chosen as sensory systems. A detailed analysis of the conveyor motion system and the frames in which the sensors are mounted was also discussed.

Chapter 4

4 MR^{2}G CIM CELL COMPONENTS

4.1 Introduction

In this chapter, the research in the field of Computer Integrated Manufacturing (CIM) as carried out at the University of KwaZulu-Natal, School of Mechanical Engineering in the Mechatronics Research and Robotics Group (MR^{2}G) Laboratory is being presented. Detailed description of individual CIM cell components developed at the laboratory is provided as well as highlighting the integration of the CIM cell components with the shop-floor control system. Various industrial applications and research for the CIM cell components is highlighted throughout this chapter.

The paradigm of engineering is undergoing a major revolution throughout the world. The use of computers and the Internet technologies has changed the methodology of engineering and manufacturing products. Traditional manufacturing has rapidly gave way to new, fast response, customer focused techniques that maximises the manufacture's return on all resources such as capital, materials, equipment, facilities and personnel. Manufactures worldwide are implementing cultural changes throughout their organizations that compliment technological advancement and facilitate the transition from mass, to lean, to agile manufacturing and reconfigurable techniques.

The required flexible, cost-effective, integrated manufacturing environments to operate in agile environments can be accomplished through a synthesis of advanced manufacturing technologies, factory automation, modern manufacturing management techniques, and information communication technology. CIM appeared as the outstanding manufacturing approach that integrated all the elements in an efficient manner. CIM was to provide the necessary flexibility to enable lower manufacturing costs, rapid change to customer demands, shortened lead times, shorter product lifetimes and increased quality of products.

Since the inception of CIM, many manufacturing companies have been investing large sums of money into advanced production facilities. These facilities include computer hardware and software, robotics, automated material handling systems, machine tools, and data management and communications equipment.

4.2 The MR^{2}G CIM Cell Components

The School of Mechanical Engineering, Mechatronics and Robotics Research Group (MR^{2}G), University of KwaZulu-Natal, has, for sometime, been involved in the research of Computer Integrated Manufacturing (CIM) Systems and its associated technologies. The research group has over a period of time developed a CIM cell as shown in Figure 4.1.

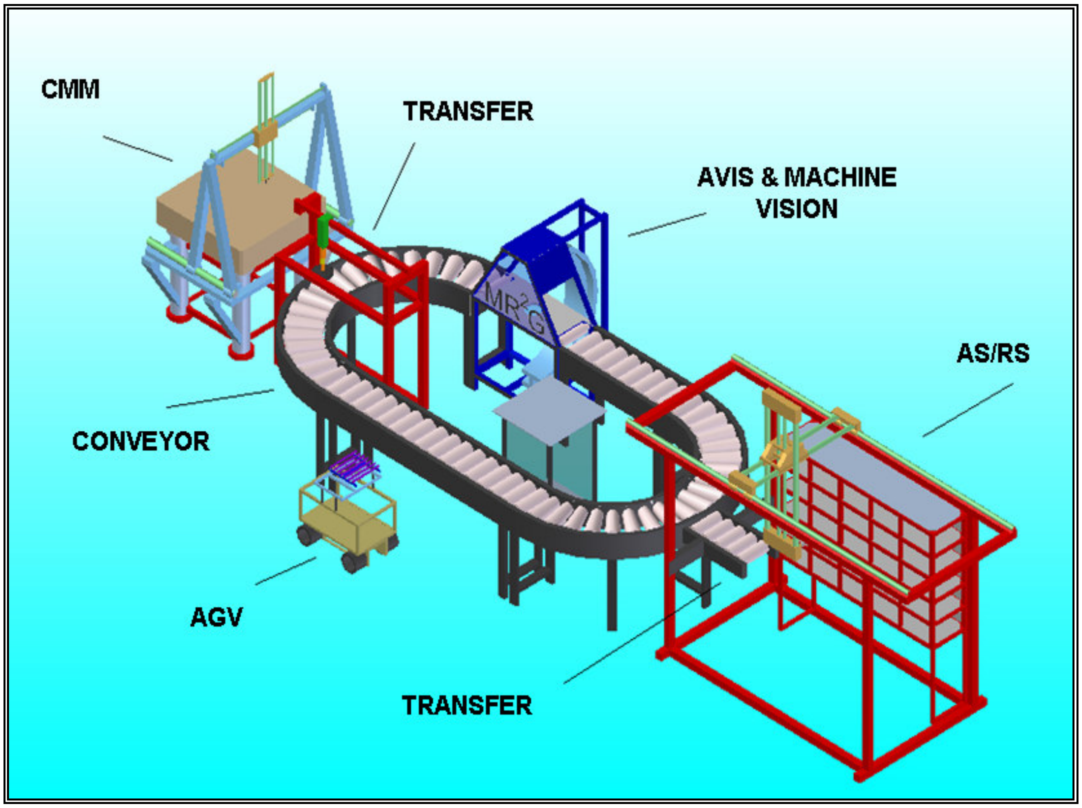


Figure 4.1 University of KwaZulu-Natal CIM Cell

The CIM cell comprised of various classes of equipment and a hierarchical shop-floor controller. Various classes of equipment include; a material processor (MP), material handling machine (MH) and material storage machines (SM). Individual pieces of equipment posses individual machine controllers to provide physical control of the devices.

4.2.1 Material Processing (MP) Equipment

The material processing equipment was the MAHO MH-400C milling machine with a retrofitted Heidenhain TNC-426 controller. This machine tool used material removal cutting process on the raw material piece using a cutting tool thus changing the shape of the work piece.

A CNC machine tool system comprises a machine control unit (MCU), and the machine tool itself. The MCU is further divided into two elements: the data processing unit (DPU) and the control loops unit (CLU). The DPU processes the coded data from some media and relays information on the position of each machine axis, its direction of motion, feed, and auxiliary function control signal to the CLU. The CLU operates the drive mechanism of the machine, receives feedback signals about the actual position and velocity of each axes. The machine tool is equipped with a visual display unit (VDU) and a foil keyboard. The VDU displays all relevant data for the work in progress or displays program memory for entry and edit.

4.2.2 Material Handling (MH) Equipment

The material handling equipments used in the cell are the automated guided vehicle (AGV) and the modular conveyor belt.

4.2.2.1 Automated Guided Vehicle (AGV)

An AGV is an independently operated vehicle that moves material along defined paths between defined delivery points or stations (Groover). A typical AGV shown in Figure 4.2 comprises of:

Control Enclosure: The electrical control enclosure includes all controls of the AGV. Normally there is a control board with an input/output (I/O) board, chopper units for drive, steer and lift motors. The design of the enclosure makes it very easy to access all the components, which makes it easier to service and troubleshoot.

Battery: The battery of an AGV is normally located above the drive unit and below the electrical control enclosure. The battery may be tractionary lead acid, gel or Nickel-Cadmium type. The location of the battery should be easy to access for maintenance as well as for the weight distribution in the vehicle. It is covered by a cover plate, which also holds it in position. AGVs uses either 24 volt or 48 volt battery capacities which could be made by having a number of 12V batteries connected in series to achieve the said capacity, however the capacity depends of type of battery, the AGV design and the type of operations.

The Drive Unit: The drive unit is located under the battery and behind the front bumper. It is an integrated unit with a drive motor and a braking system. The drive unit is mounted on a mounting plate, which is attached to a turn table. A steering motor is mounted to the mounting plate and rotates the complete unit when running.

The Lift Unit: The lift unit is mounted on a cross-tie welded to the fixed mast. The lift unit is an electromechanical design consisting of a ball screw with a ball nut, a direct current (DC) motor, worm gear box and a brake.

The Bumper Unit: The bumper unit is a safety device that should stop the AGV immediately if it is obstructed by an object. The bumper unit is normally designed with a polycarbonate shield around the front part of the AGV. The shield is mounted on two hinges, which are fixed to the AGV chassis. The shape of the bumper shield is controlled by strings attached to the shield and AGV chassis. The main purpose of the bumper is to protect people and the AGV itself from damage. It is normal for a bumper in an industrial environment with combined AGV traffic and manual fork lifts, manual pallet lifters operated manually, to be damaged and worn as it is obstructed.

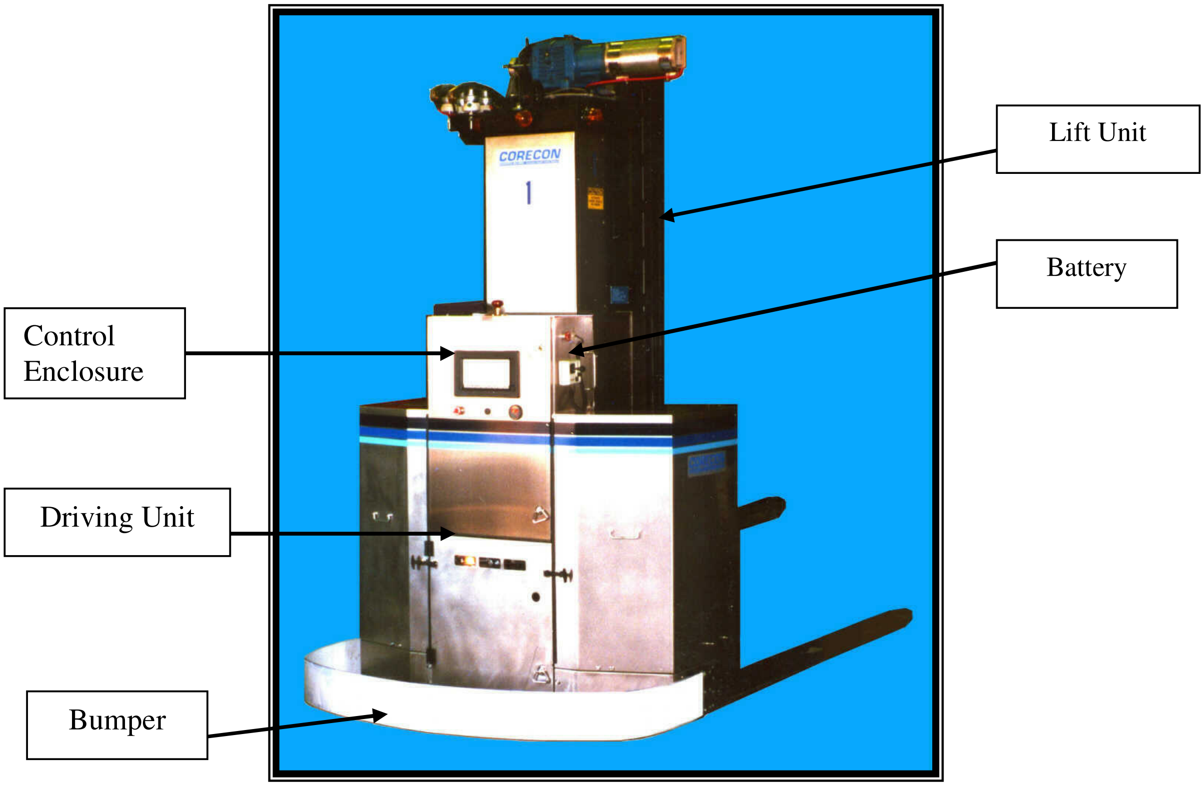


Figure 4.2 Typical AGV and Various components (Core con)

4.2.2.2 AGV Navigation Systems

The desired path along which AGVs moves may be a fixed-route, semi-fixed route or an arbitrary route. Trajectory recognition of the route should be accomplished by the AGV navigation system. Fixed routes require the installation of a fixed action guide like an energized cable or a passive one like a reflecting strip painted on the shop floor (see Figure 4.3).

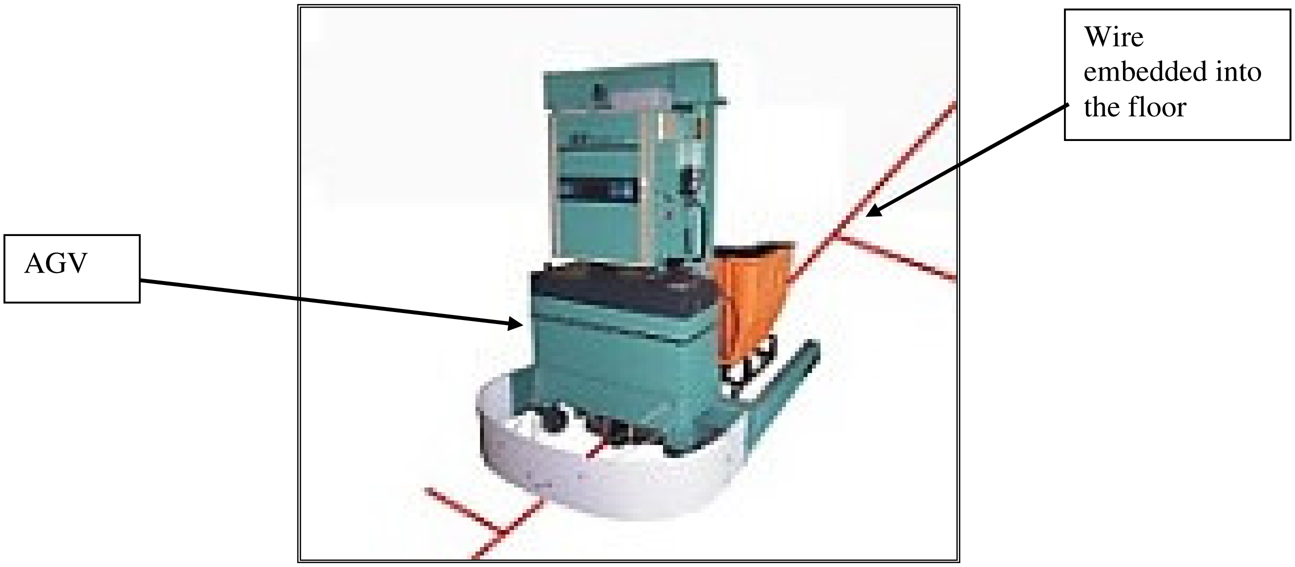


Figure 4.3 AGV controlled by wires embedded in the floor (Ed Red)

A semi-fixed route may be specified by some markings at strategic locations on the plant floor. These marks can be like bar codes, magnets or some other type of artificial landmarks depending on the guiding method. During the motion of the vehicle between two markings, the navigation system should update the absolute position of the vehicle based on the sensor reading and this absolute position is further corrected when a specified marking is identified.

In general, arbitrary routes require the use of more complex position determination techniques such as global positioning system (GPS), recognition of the surrounding by image processing, use of gyroscope, sonar, laser beacon or map-based position detection (Van Brussel). These techniques are used to determine the absolute position of the vehicle on the shop floor or in plants. For a known surrounding, map comparison is employed, and is aided by one or more methods for recognition of the surrounding like sonar, laser beacons, and video cameras. Recently some of these techniques have been effectively employed for the navigation of the AGVs on industrial shop floor as shown in Figure 4.4.

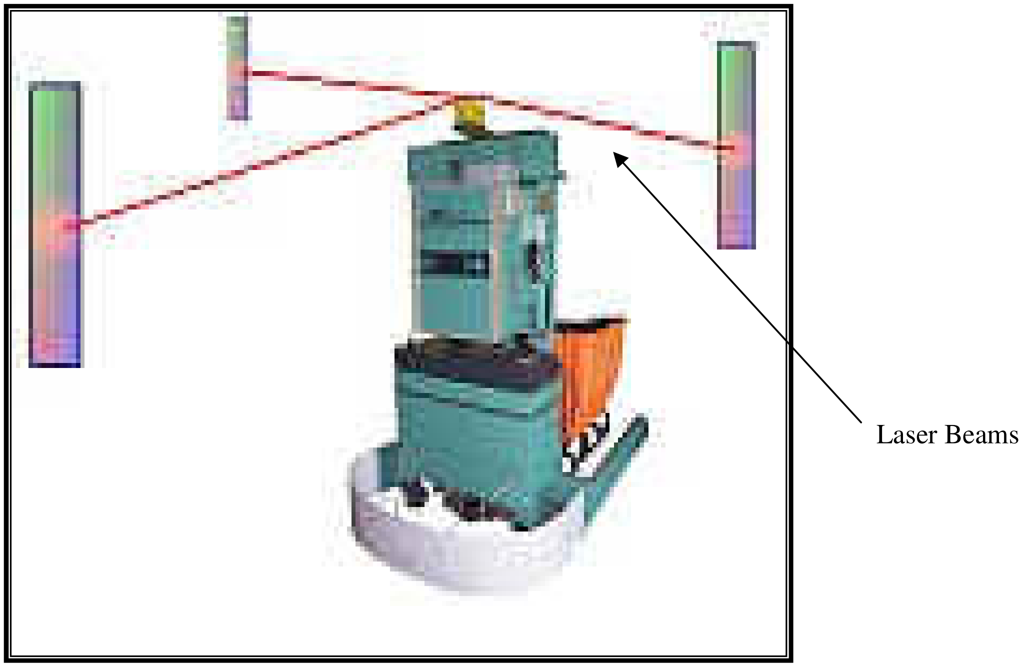


Figure 4.4 Laser Scanner Guidance for AGV Control (Ed Red)

4.2.2.3 The AGV Developed at the University of KwaZulu-Natal

The AGV developed at the University of KwaZulu-Natal; (Figure 4.5) was driven by four permanent magnet DC motors, one for each wheel. Each motor had the rubber wheels that were mounted at 45 degrees to make the motion of the vehicle more flexible. The rubber on the wheels provided traction on the ground. The drive circuits utilizing the LM12 power operational amplifiers controlled the power delivered to the DC motors by interfacing between the low current computer generated signals and the high current demanding motors. Two 12V lead acid 60 Amp-hour accumulators were fitted aboard the AGV to provide power for the operation of the speed and directional control circuits. This was more sufficient to allow the AGV to be used for approximately thirty (30) minutes before being recharged. The technique employed is not to allow the battery to be fully discharged before trickle recharging to fully charging it when AGV is docked. This charging technique considerably extended the life span of the battery. The positional guidance system of the AGV was achieved by a placing a black adhesive tape on the floor as per desired vehicle path. This method required adequate lighting as well as light sensing capabilities on-board the AGV. The principle of operation of this guidance technique was that the AGV follows a black strip that contracts against the adjacent floor. Light sensor modules mounted on the AGV detected the lateral position of the AGV relative to the black strip and through the output circuitry, sent a signal to the controlling on-board computer (Khan).

The resistance of the light detector resistor (LDR) varies with the intensity of the incident light, thus the resistance of the LDR increases with the reduced intensity of the incident light. Since the guide path was a black strip, it absorbed the light incident on it and this phenomenon was used to detect the position of the AGV relative to the guide path.

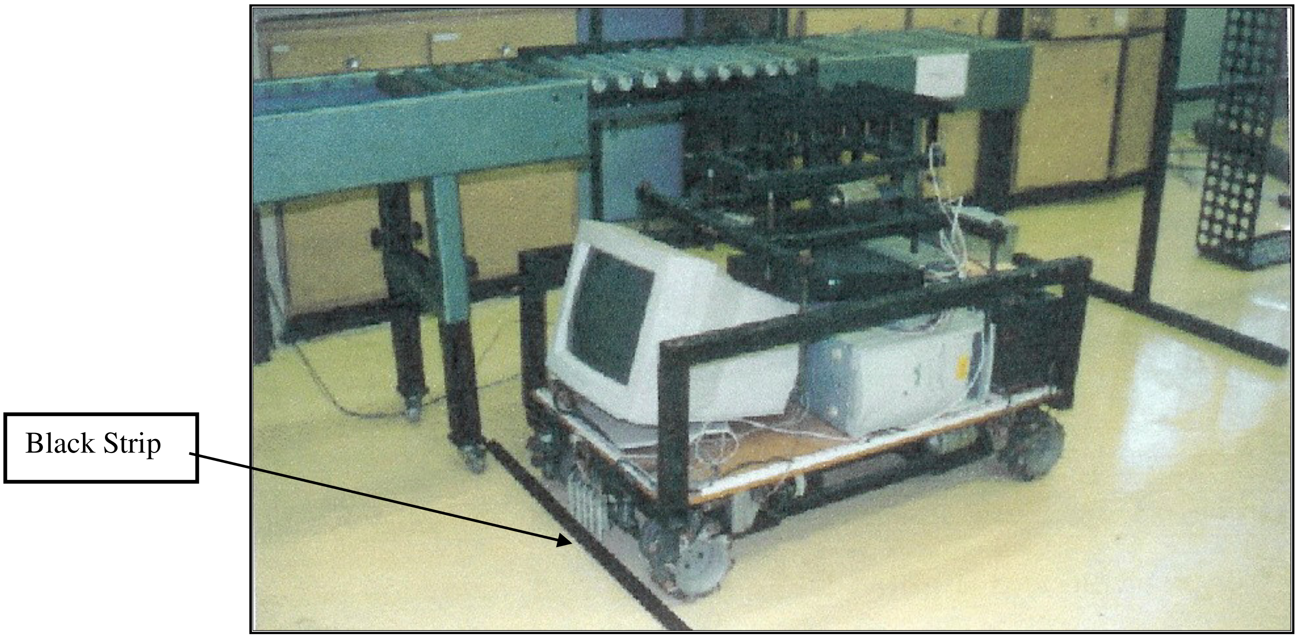


Figure 4.5 The AGV developed at the University of KwaZulu-Natal

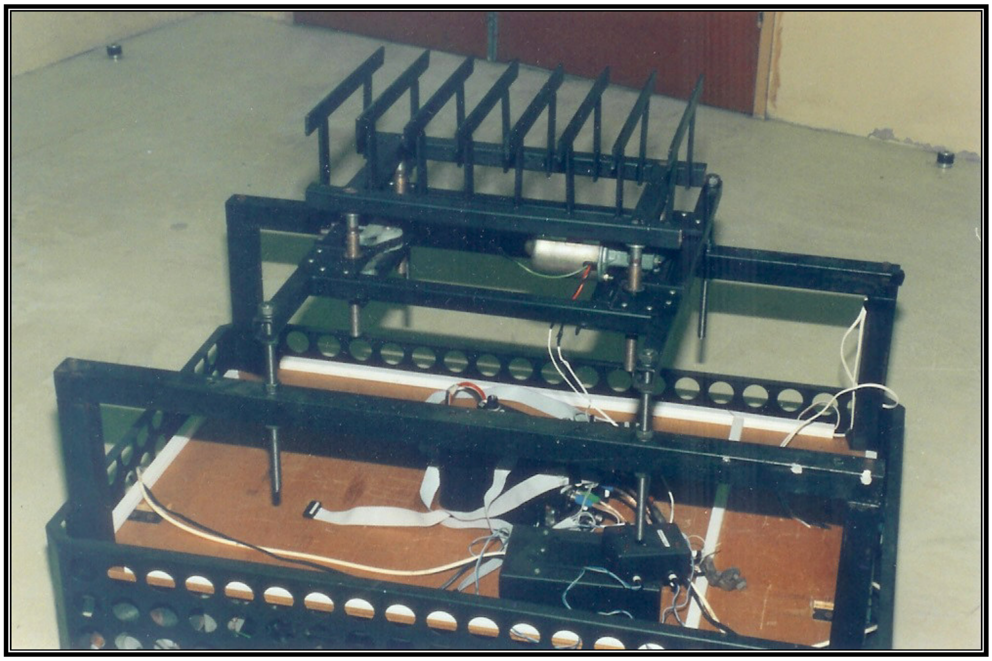


Figure 4.6 Mooring platform mounted on the AGV

The AGV comprised of a mooring platform (Figure 4.6) which enabled a pallet containing a component to be positioned on the AGV for transportation. A mooring circuit was designed to allow the platform to move in a vertical plane to enable loading of a pallet from the conveyor (Figures 4.7 and 4.8).

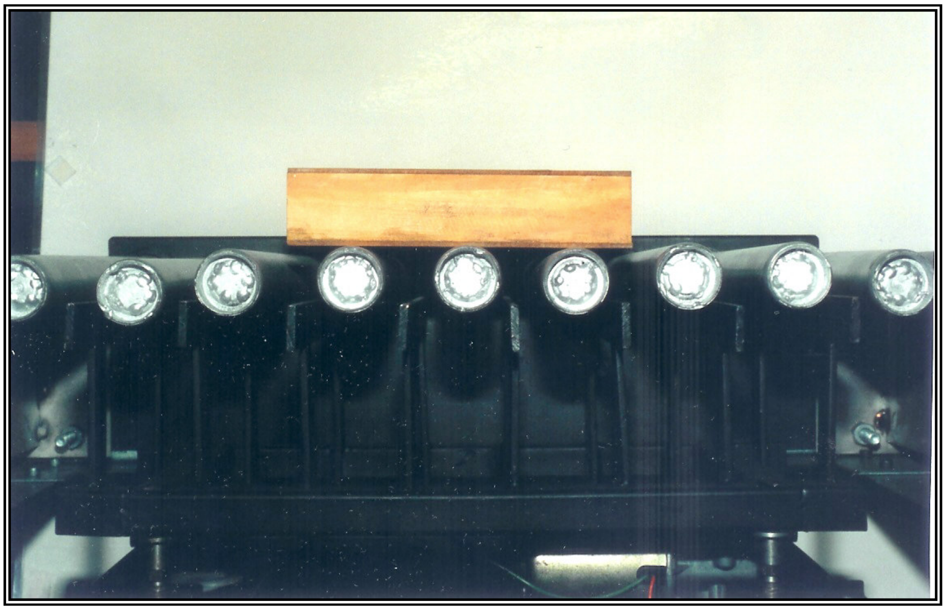


Figure 4.7 Pallet on the conveyor with AGV underneath the conveyor to pick up the pallet

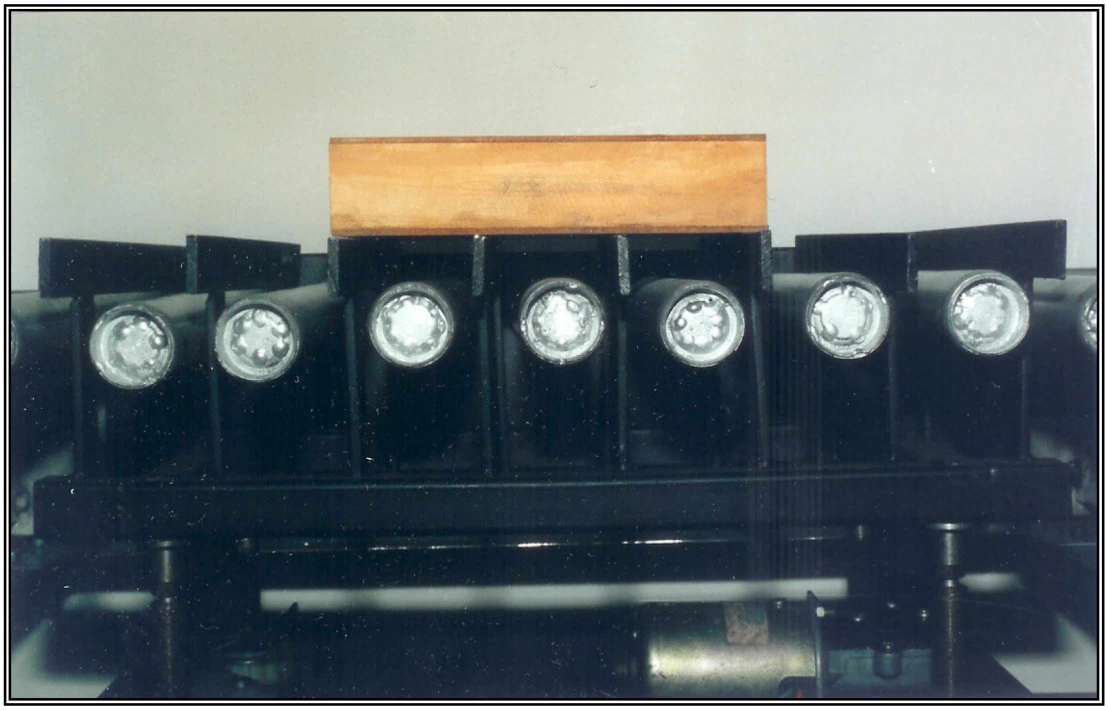


Figure 4.8 Material support beams are raised and the pallet is loaded onto the AGV

4.2.2.4 AGV Applications

AGVs were introduced in industry around 1950s and their use has grown enormously since then as the number of areas of application and variation in types has increased significantly. AGVs can be used in inside and outside environments, such as manufacturing, distribution, trans-shipment and (external) transportation areas. In manufacturing areas, AGVs are used to transport all types of materials related to the manufacturing process. Examples of these environments are distribution, transhipment and transportation systems (Ed Red). Warehouses and cross docking centres are examples of distribution areas. AGVs are used in these areas for the internal transport of pallets between the various departments, such as receiving, storage, sorting and shipment areas (see Figure 4.9). At transhipment systems, such as container terminals, AGVs take care of the transport of products between the various modes of transport. The AGV systems can provide benefits to both the port and its customers by executing transportation requests between ship vessels and inland transportation. AGVs can also be used in outdoor transportation process such as transportation system is an underground automated transportation system with AGVs travelling in tubes between compartment and at an airport as shown in Figures 4.10. AGVs have also been used for fuelling, cleaning and parking of bus fleets as shown in Figure 4.11. AGVs have also been known to be used in household environments as shown in Figure 4.12.

Figure 4.9 AGV used in a Manufacturing Environment

Figure 4.10 AGV used as a Shuttle in Railway Station Tubes and Airports (Ed Red)

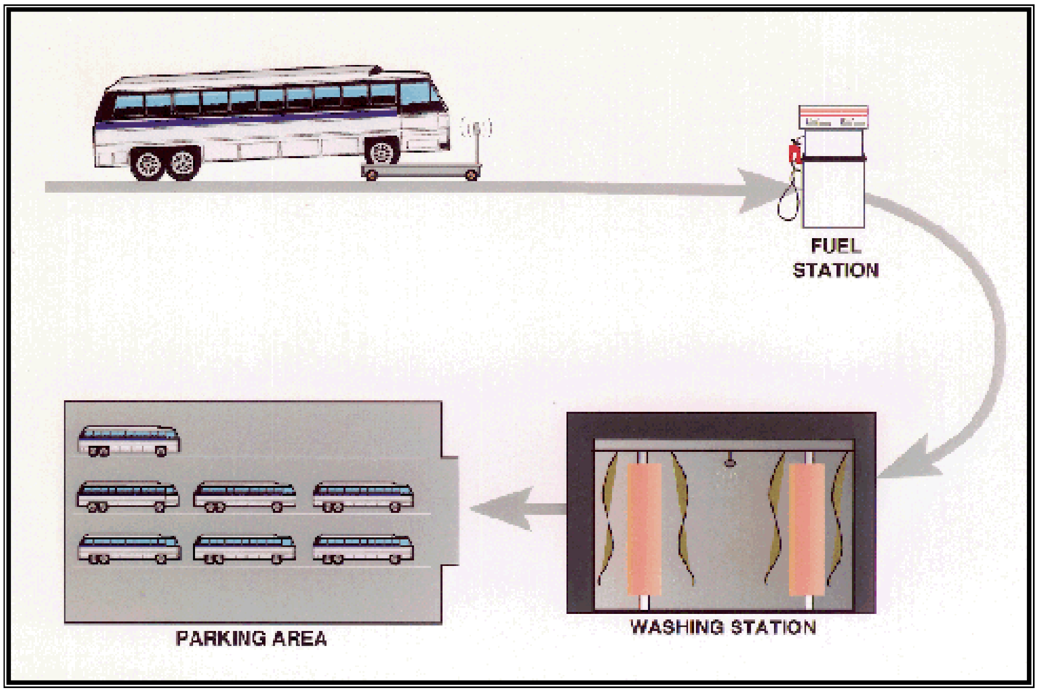


Figure 4.11 AGV used for fuelling, cleaning and Parking Vehicles

Figure 4.12 AGVs used in a household Environment (Ed Red)

4.3 The Industrial Robot

An Industrial robot is re-programmable, multi-functional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks" (Robotics Institute of America). Industrial robots are distinguished from other types of machinery mainly on the basis of their programmability and adaptability to different tasks. Robots are therefore probably the most demanding type of equipment concerning the software and control aspects. There is also a desire to handle more complex situations since it is likely that future applications will demand even more flexible systems. Apart from flexibility there is also a strong demand for efficiency since performance has been the primary goal in the still very active research field of robot control.

A PC based PUMA MK2 560 series jointed arm robot was used to load and unload parts for the AS/RS, the conveyor belt and the CNC Milling (Figure 4.13). The robot was a six degree-of-freedom (DOF) elbow manipulator which consisted of three large joints that formed the arm and three small joints that formed the wrist. The end-effector of the robot arm could reach any point within its working envelope from any direction.

The six degrees of freedom were controlled by six brushed DC servo motors, each coupled with a 500-1000 count 3 channel encoder and a potentiometer. The robot could determine its global position from the given feedback information. Potentiometers were used to establish the robot's absolute position at initialization. The incremental encoders provided both position change and velocity signals for the servo system, there are sampled approximately 32 times during each 28-milliseconds window. PUMA 560 robot was designed to meet the needs of a flexible manufacturing environment and can therefore adapt to a wide range of applications. The robot controller comprised the Pentium 2 500MHz computer and the internet control which formed part of the supervisory control. Three interface cards, two Advantech PVL 832 and one Eagle PC 30GA were used to provide online interactions with the user, the graphical user interface (GUI) as well as sub-tasks coordination with the servo control as well as interface cards.

Figure 4.13 The PUMA Robot

4.3.1 Uses of Robots

There are many uses of robots today, and more are anticipated for the future. Here is a list of some areas;

Industrial manufacturing: Industrial robots gained wide use in manufacturing plants during the 1970s. Especially the automotive industry has replaced many human labourers with robots. The typical industrial robot is programmed to carry out one special task, such as welding or painting.

Mining: Robotic vehicles are deployed within the mining industry, e.g. in Australia and Sweden.

Unmanned aerial vehicles (UAV): Flying vehicles are primarily in use for military reconnaissance. The Predator, an Unmanned Aerial Vehicle (UAV) was deployed in the 1999 Kosovo air campaign as well as over Afghanistan from 2001.

Underwater robots: Autonomous underwater vehicles (AUVs) have been used for scientific, military and commercial purposes in applications such as ocean surveying as shown in Figure 4.14, unexploded ordnance hunting, cable tracking, inspection and repairs.

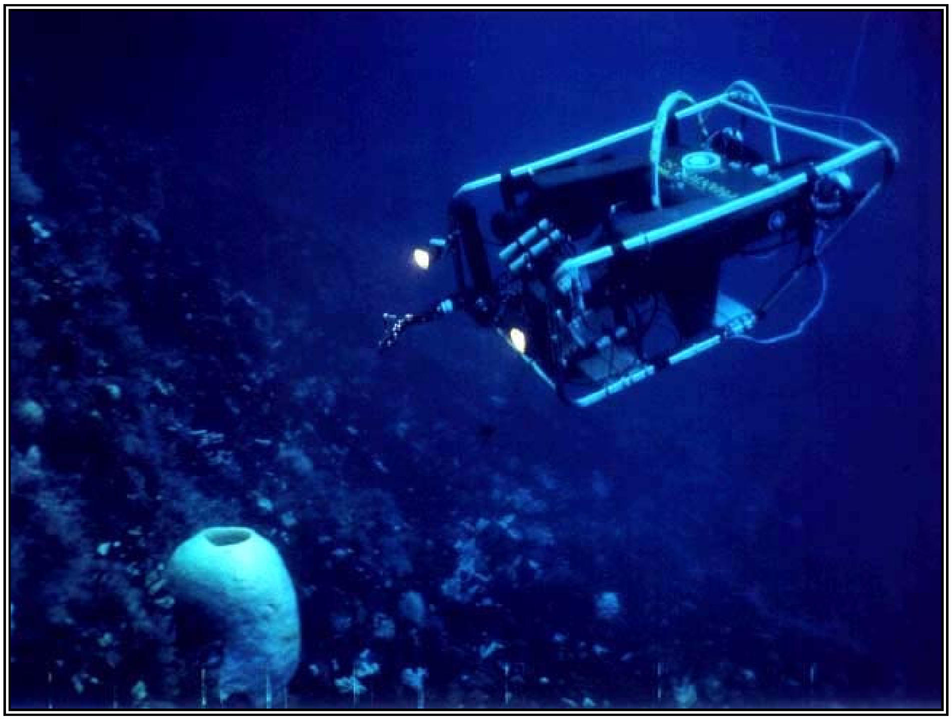


Figure 4.14 Remotely Operated Vehicle (ROV) in Antarctica operating under water (Garmat)

Service robots: A service robot is a system that services humans where the cost/performance ratio is beneficial, e.g. the automated lawn mower (see Figure 4.15), toilet cleaner (Figure 4.16) and garbage collection (see Figure 4.17). A sophisticated type of service robot is the personal assistant robot. These are not common today but are expected to have a great future. This is motivated by an aging population in the West and Japan. Robots could aid the elderly with household tasks such as cleaning, cooking, and even feeding. In hospitals, food-plates and medicines can be delivered to the rooms, and in office environments mail can be delivered to the staff. Another area of service robotics is acting as tour-guides in museums and similar places.

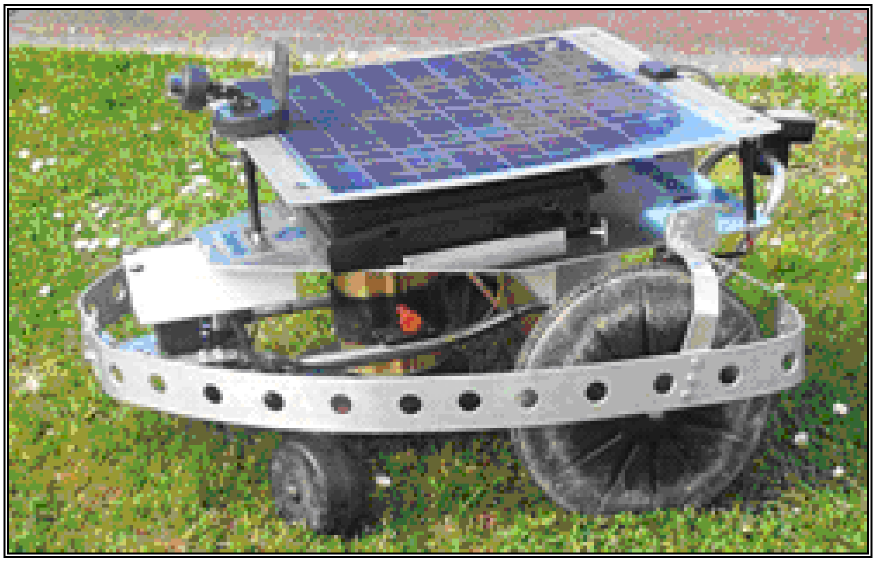


Figure 4.15 Internet Controlled and Monitored Lawn Mower (Bright et al, 2003).

Figure 4.16 Scrubmate Robot cleaning the toilet (Burgard)

Figure 4.17 Garbage Collection Robot (Balakirsky)

Bomb and mine disarming, hazardous environments: Tele-operated robots are in widespread use at tasks where a human would be at risk. For example the police use them for disarming bombs.

Space missions: The use of robots in space exploration has been rather well-known to the general public after the successful missions to mars. First space mission robot was the Sojourner in 1997 as shown in Figure 4.18, then the Spirit and Opportunity in 2004 [NASA]. There are other uses of robots in space, e.g. in unloading of cargo on-board space shuttles.

Figure 4.18 The Rover (NASA)

Edutainment robots*:* robots have also been used for entertainment, hobbies (toys, games and building sets) and education e.g. *Sony's AIBO* dog as shown in Figure 4.19.

Figure 4.19 Sony's AIBO dog (Sony)

4.3.2 Characteristics of Robotics

Robotics is a multi-faceted field covering many different aspects. Here consideration is done at three of these;

(i) Mobility: Real robots always have moving parts. Mobile robots can move entirely in space normally utilising wheels, legs or tracks. If the robot acts in the air or underwater, surely other methods of transport are used. Outdoor robots generally need mobility as shown in Figure 4.20.

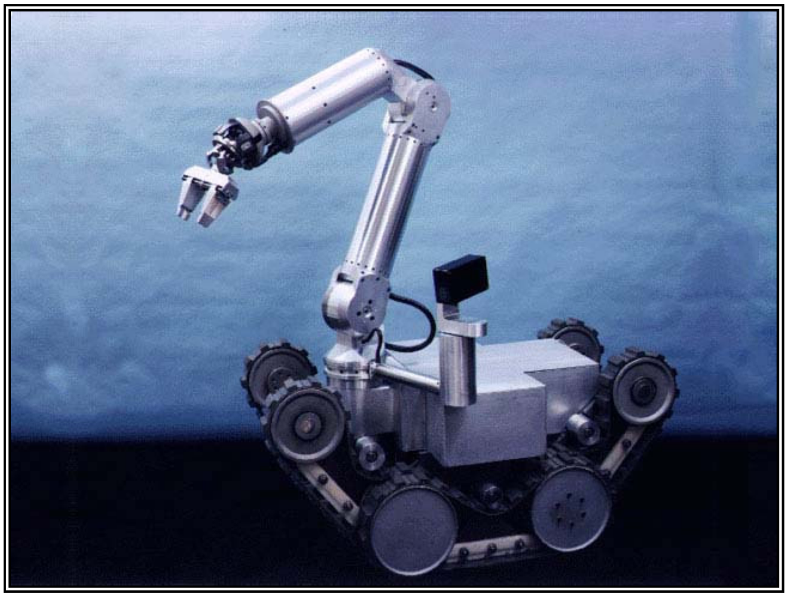


Figure 4.20 Mobile Robot

(ii) Autonomy: To be autonomous, the robot needs to be able to adapt reasonably well to unexpected changes in the environment. The primary motivations for the industrial robots' wide use today its high degree of repeatability that ensures a homogeneous quality. In order to achieve a level of autonomy and awareness of the world surrounding, it is necessary for the robot to use sensors such as sonar, cameras etc. to obtain the phenomena (see Figure 4.21).

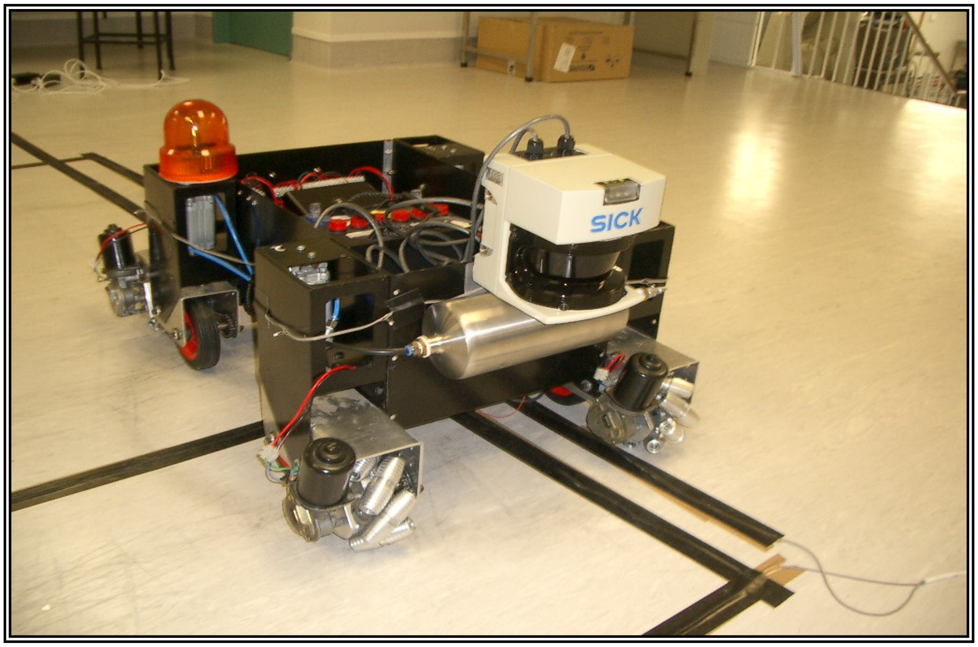


Figure 4.21 Mecanum Wheeled Autonomous Mobile Robot (Kumile and Tlale, 2005)

(iii) Versatility: Robots are often built to perform one special task or another and are made robust. . Robots such as a personal assistants, or *robotic butlers*, should in contrast be able to carry out a wide range of tasks, this puts higher demands on both their hardware and software designs. Researchers have built anthropomorphic robots (humanoids aka androids) as shown in Figure 4.22 are poised for higher goals, as they strive to mimic the capabilities of human beings [Honda].

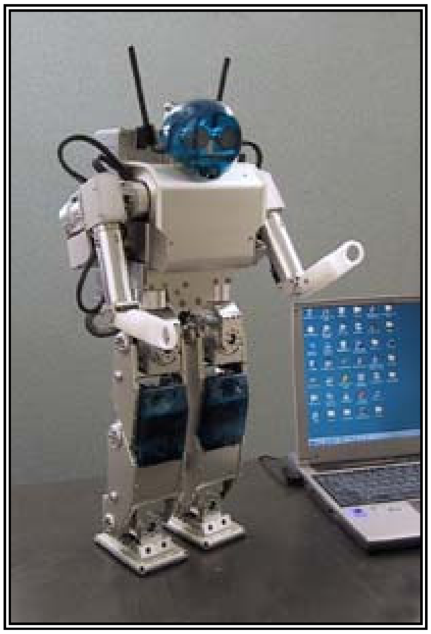


Figure 4.22 Humanoid Robot (Honda)

4.4 The Conveyor Belt System

Conveyors is either a fixed or portable devices used for transporting materials between two fixed points, through intermittent or continuous movement [Groover]. Conveyors are usually employed where the workflow is relatively constant. Industrial conveyors can be classified into several categories, such as bulk material and unit handling conveyors, accumulating and non-accumulating conveyors, and fixed and portable conveyors.

Bulk conveyors are those employed to handle coal, ashes, cement grains, flour sand, and almost any material that is not packaged, crated, or otherwise handled in unit loads. The unit conveyors are those designed to handle small pieces in containers weighing from few ounces to large units such as filled pallets, crates, or assemblies weighing tons. The powered roller conveyor system can be adopted where distances travelled by goods can be increased and the speed at which the pallet can be controlled by varying the motor speed. The roller elements of tubular design encased roller bearings positioned at each end. The bearings are used to minimize friction and noise during conveyor system operation. The power roller conveyor systems was driven by DC electric motors with belts interlinking the drive mechanism, where power is transmitted from a belt, to a roller, and back to another belt (see Figure 3.1). This interlinking carried on along the whole length of the conveyor section to provide power transmission. The roller conveyor systems comprised of rollers that are perpendicular to the direction of travel. The conveyor system consisted of six different tracks combined to form the oval configuration (ref. Figure 3.2). The conveyor sub-system comprised of two straight sections and four sections consisting of 90 semi-circular sections. Each conveyor section was driven by a 12V DC servo-motor and there were ten servo motors required to drive the initial and frictional loads in both directions in the conveyor system.

4.5 Coordinate Measuring Machine (CMM)

CMM are electro-mechanical systems designed to traverse a measuring probe across a surface of a work piece to determine its point coordinates. Essentially, the CMM is comprised of four critical components: the machine structure including bed, the measuring probe, the control system, and the integration software. CMMs are available in a wide range of sizes and designs with a variety of probe technologies as shown in Figure 4.23.

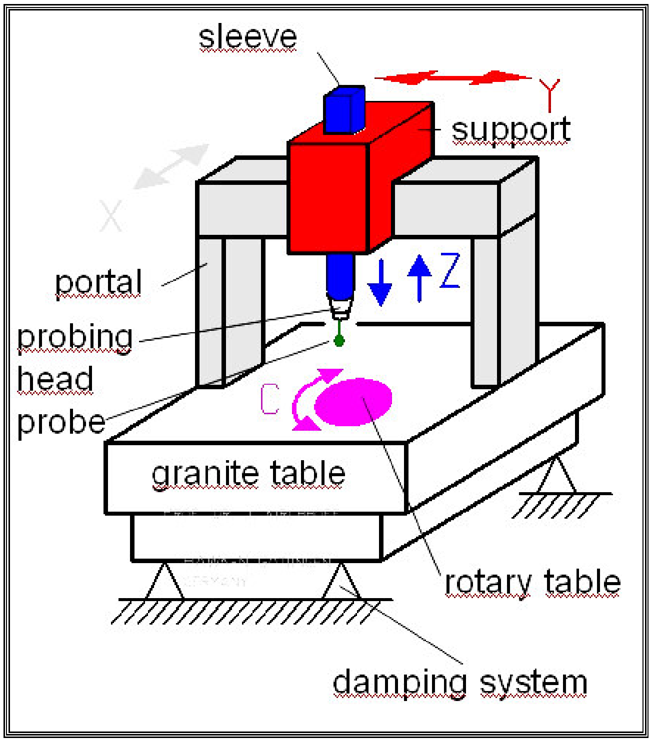


Figure 4.23 (a) Illustration of CMM Components

During the operation of the CMM process, the object to be measured is normally probed point by point using a stylus with a spherical (most commonly) ruby ball tip. At the moment of an each probing contact, the XYZ coordinates of the ball tip are measured and stored in a computer memory. The sensor which provides the connection between the object surface and the 3D length measuring system of CMM is called ‘‘probe’’. There are groups of contacting (touch) and non-contacting (optoelectronic) probing systems. A number of different optoelectronic probes are used, though triangulation probes are most popular. Contacting probes are categorized into tough trigger and measuring systems. The probe is one of the most important factors influencing CMM accuracy. All the touch trigger probes contain a three base spring-tighten setting mechanism (a six point kinematical mechanism) by which the stylus is electrically fixed in five or six spatial degrees of freedom. In the basic version this mechanism is designed as a group of electrical contacts (see Fig. 4.24a). When the stylus touches a workpiece, the electrical contact is opened and a trigger pulse is created and sent to the computer resulting in coordinates reading. Though there are many different designs of this kind of probes, the generation of the trigger pulse is always strictly connected with triploid structure of the settings [Dobosz].

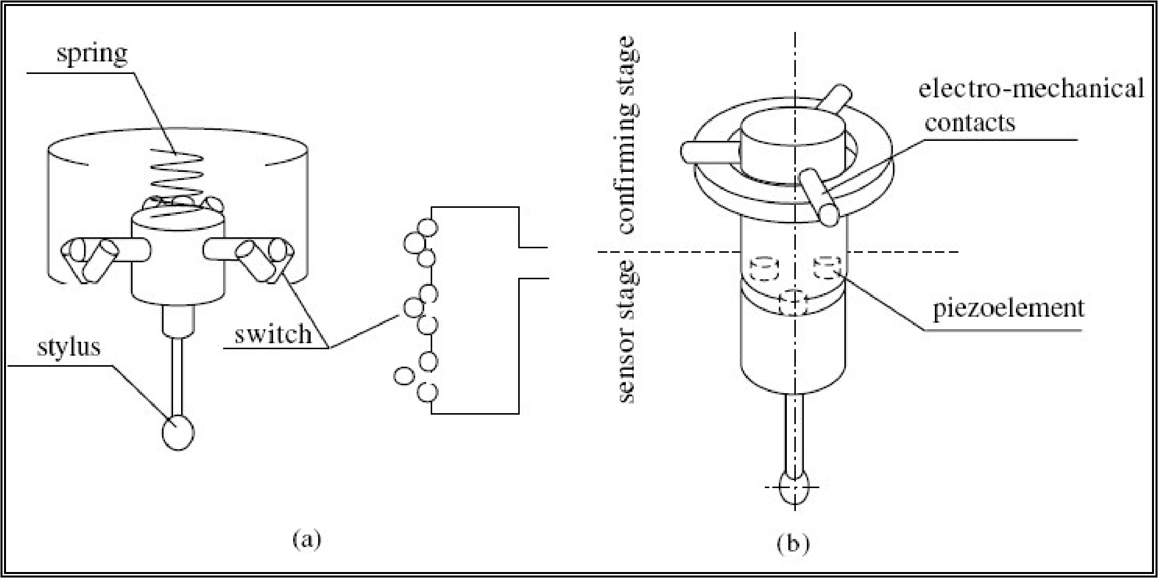


Figure 4.24 Scheme of Switching Probes (a) one stage with electro switch transducer (b) two stage with three piezo elements

4.5.1 Types of CMM Configurations

The type of configuration for a CMM determines its measuring parameters such as flexibility, time or throughput of measuring process, maximum measurable work piece dimension and cost. Most of these configurations can be controlled manually by an operator or by a program of some sort.

4.5.1.1 The Bridge Type

In the bridge style machines, the arm is suspended vertically from a horizontal beam that is supported by two vertical posts on a bridge arrangement.

The machine x-axis carries the bridge, which spans the object to be measured. There can be inconsistencies I the motion of the vertical posts while spanning the table length, causing the bridge to twist or yaw. The error can be corrected using a positive position feedback control system or a central drive mechanism which moves both posts at the same time. Given the rugged construction of this machine, it has a higher natural frequency which improves the dynamic response of the machine. This type of CMM can have a smaller footprint which is suitable for clear room or design laboratory type facilities.

4.5.1.2 The Gantry Type

The class of machines is used for large part sizes which can span 4 metres or more. Gantry style machines employ a frame structure raised on side supports so as to span over the object to be measured or scanned. A horizontal beam traverses the length of the measured object. It is powered by with dual drives so as to minimise the yaw or twisting of the side supports during traverse. A measuring arm is mounted on this horizontal beam that moves along the width of the object being measured. Gantry machines have a rugged construction compared with other CMMs to offset the deformation caused by twisting and the weight of the measured part on the foundation. Additional precision can be enhanced using thermal compensation and combination of air bearings and high accuracy linear guide-ways.

4.5.1.3 The Cantilever Type

In cantilever style machines, a vertical arm is supported by a cantilevered support structure. This open configuration allows for easy operator access to the object being measured. Heavy parts can be measured by placing them on a fixed table. However, due to the overhanging cantilever structure it has a lower system natural frequency affecting the speed of measurement. This system is suitable for longitudinal parts that fit along the length of the table and have a smaller dimension in the other two axes.

4.5.1.4 The Horizontal Arm Type

Horizontal arm machines are widely used in the automotive industry. In this configuration the arm that supports the measuring probe is horizontally cantilevered from a movable vertical support. It is also available in dual arm configurations which tend to limit the dynamic stiffness of the machine affecting speeds of measurements; however this error can be compensated with software correction.

4.5.1.5 The Articulated Arm Type

An articulated arm configuration is used for portable, or tripod mounted style machines. The articulating arm allows the probe to be placed in different directions with respect to the object being measured. These systems contain a series of counterbalanced six degrees-of-freedom linkage arms. Each of the arms is provided with precision rotary transducers that encode the rotary motion of the linkages and calculate coordinates in 3D space.

The measuring envelope of this type of system is spherical, enabling measurement of hard to reach locations within components. These types of systems are made of light weight alloy material for high rigidity and low weight. Articulated arm type CMMs are portable, versatile with a wide range of accessories for on-site measurement tasks.

4.5.2 The CMM Developed at the MR^{2}G Laboratory

The CMM at MR^{2}G laboratory was developed to provide precision measurements in three-dimensional (3D) cartesian coordinate space. The CMM as shown in Figure 4.25 comprise a vertical column that rides on a bridge beam and carries a touch-trigger probe. Touching the probe to the surface generates an accurate measurement of the component dimensions. The CMM utilises digital readouts, air bearings, part probes mounted on a granite table to enable accurate measurements. The CMM was controlled by a PC based control system.

Figure 4.25 The CMM Developed at the MR^{2}G Laboratory

4.6 The Automated Visual Inspection System (AVIS)

Machine vision is the capturing of an image (a snapshot in time), the conversion of the image to digital information, and the application of processing algorithms to extract useful information about the image for the purposes of pattern recognition, part inspection, or part positioning and orientation. Machine vision systems are emerging as more and more popular solutions for industrial production, either as robot vision systems or as automated inspection systems. The developed AVIS comprises of a digital camera, a part manipulation system to enable template matching of the manufactured parts to the required specifications (Figure 4.26).

Figure 4.26 Automated Visuals Inspection System

4.7 Automated Storage and Retrieval Systems (AS/RS)

An Automated Storage and Retrieval Systems (AS/RS) is a combination of equipment and controls which handles, stores, and retrieves materials with precision, accuracy, and speed under a defined degree of automation (Materials Handling Institute). An efficient storage and retrieval of components, tools, raw materials and subassemblies is required in modern manufacturing systems like automated factories, distribution centres, warehousing and non-manufacturing environments. It is a major material handling system widely used in industry today. The AS/RS is widely used in numerous manufacturing factories and distribution centres in the world.

A typical AS/RS is composed of multiple parallel aisles of racks with storage cells (slots), a storage/ retrieval (S/R) machine for each aisle, and input/ output (I/O) station. The design of AS/RS involves the determination of the number of S/R machines, their horizontal/ vertical velocities and travel times, the physical configuration of the storage racks, etc. The S/R machine is usually made up of one shuttle and a mechanism to move the shuttle from the I/O port to another location on the storage rack.

4.7.1 The Developed AS/RS

The developed AS/RS comprised of vertical storage racks, single aisle system and stacker system to transport products between rack locations and pock-up and delivery (P& D) stations (Figure 4.27). The AS/RS was controlled by a computer for its operations and interactions with other CIM cell components. This "unit load" system could be used for raw material and finished product storage and retrieval. Unit load offers high throughput, maximum space efficiency and real-time inventory control. AS/RS provided a cost effective alternative to conventional buffer storage or re-sequencing conveyors.

Figure 4.27 Automated Storage and Retrieval System

4.8 Shop Floor Control Architecture and Functionality

The Shop floor control system (SFCS) for discrete part manufacturing has been widely described by many researchers, which have led to several framework to solve the overall shop floor control problem. These frameworks have been called control architectures, control structures, and control models, etc. [Chang et al.,].

Various control architectures have been presented as can be seen from Figure 4.30. In general, four main decomposition approaches – centralized control, hierarchical control, hybrid control, and distributed control architectures.

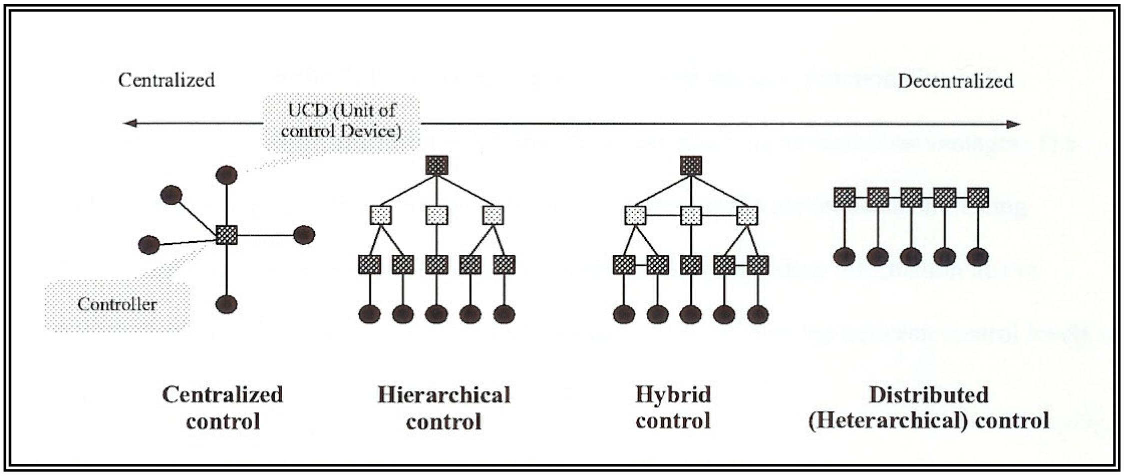


Figure 4.28 Taxonomy of a shop floor control architecture

4.8.1 Centralized control

In a centralised control architecture, one controller controls the entire stock of equipment and maintains global information to record the activities of the whole system. In other words, a single shop floor controller is responsible for scheduling part across the equipment, checking resource status in the system, downloading control programs, and monitoring the manufacturing progress.

4.8.2 Hierarchical Control

A hierarchical control architecture consists of a control system which has several levels of authority. At each level, the functionality and objectives are defined.

4.8.3 Distributed/hetararchical Control

In distributed control architecture, each equipment controller cooperates through communication to pursue system goals without the master/slave relationship employed in the hierarchical control architecture.

4.8.4 Hybrid Control

Hybrid control architecture is a combination of the hierarchical and distributed approaches. A combination of these architectures is utilized to simplify the flow of data and also to allow more global decision-making at different levels. Under the simulation-based control environment, any of the above control architectures may be adopted. Given the number (compared to those used in industrial settings) of CIM components utilized, a two level (shop and equipment) hierarchical shop floor control system model was adopted to be utilised in this research.

4.9 Chapter Summary

In this chapter, the research in the field of CIM as carried out at the University of KwaZulu-Natal, School of Mechanical Engineering in the Mechatronics Research and Robotics Group (MR^{2}G) Laboratory was presented. Detailed description of individual CIM cell components developed at the laboratory was provided as well as highlighting the integration of the CIM cell components with the shop-floor control system. Various industrial applications and research for the CIM cell components was highlighted throughout this chapter.

Chapter 5

5 MECHATRONIC SENSORS AND SIMULATION TOOLS

5.1 Introduction

In this chapter a description of a mechatronic sensory system is provided. The photoelectric proximity sensors, vertical scanner and the bar coding system will be discussed. An overview of simulation and modelling techniques and tools used in manufacturing systems is provided. Aspects of multi sensor data fusion techniques are discussed. A comprehensive overview of commercial simulation software tools available is discussed.

5.2 Sensors

A sensor is a device in a mechatronic system that detects a change in a physical stimulus and turns it into an electrical signal that can be measured or recorded by the system [Histand and Alciatore]. The term sensor should be clearly distinguished from transducer. The latter is a converter of one type of energy into another, while the former converts any type of energy into an electrical signal. An example of a transducer is a loudspeaker which converts electrical signals into variable magnetic field and, subsequently, into acoustic waves. Transducers maybe used as actuators in various systems or maybe parts of sensors. A sensor does not function by itself; it is always a part of a larger system which may incorporate many other detectors, signal conditioners, signal processors, memory devices, data recorders, and actuators as shown in Figure 5.1. Sensors maybe positioned at the input of a device to perceive the outside effects and to signal the system about variations in the outside stimuli. Sensors maybe also be an internal part of a device which monitors the devices' own state to cause appropriate performance.

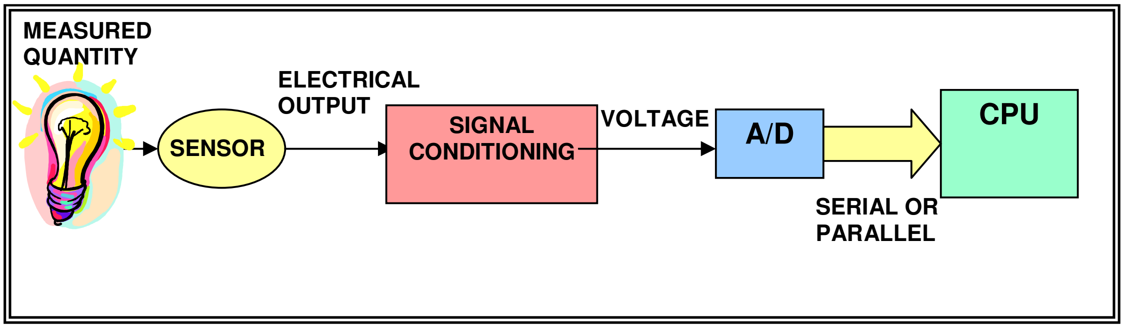


Figure 5.1 Typical Sensor Circuit

Sensors maybe of two kinds: *passive* and *active*. A passive sensor directly generates an electrical signal in response to an external stimulus. Examples of passive sensors are a thermocouple, pyro-electric detector, and a piezoelectric sensor. Active sensors require external power for their operation called excitation signal. The excitation signal is modified by the sensors to produce the output signal. Active sensors are sometimes called parametrics and their examples are a thermistor, pressure sensors and displacement sensors

To illustrate a place of sensors in a larger system, Figure 5.2 shows a block diagram of a data acquisition and control device such as a car or a space ship (Fraden). Data is collected from an object by a number of sensors; some of them (2, 3, and 4) are positioned directly on or inside the object. Sensor 1 is a non-contact sensor and it monitors the internal conditions of a data acquisition system itself. Some sensors (1 and 3) cannot be directly connected to standard electronic circuits because of inappropriate output signal formats. They require the use of interfaces devices such as signal conditioners etc. Sensors 1, 2, 3 and 5 are passive as they generate electric signals without energy consumption from electronic circuits. Sensor 4 is active, as it requires an operating signal that is provided by an excitation circuit. Electrical signals from the sensors are fed into a multiplexer (MUX), which is a switch or gate used to connect sensors one at a time to an analogue-to-digital converter or directly to a computer, if the sensors produce signals in a digital format. The computer controls a multiplexer and an A/D converter for the appropriate timing or it may also send control signals to an actuator that acts on the object. The system contains some peripheral devices and a number of devices not shown on the diagram such as filters, sample-and-hold circuits, amplifiers, etc.

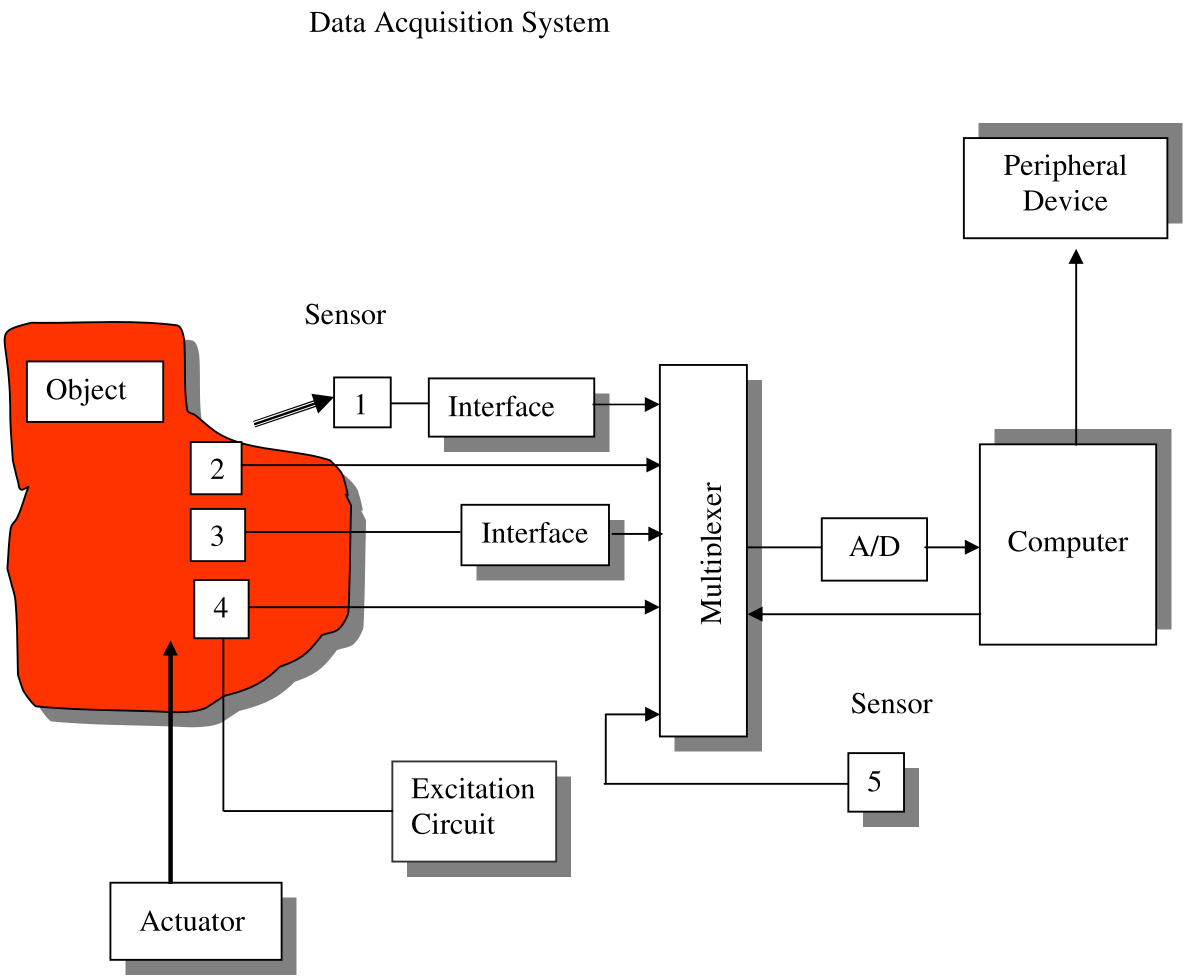


Figure 5.2 Positions of sensors in a data acquisition system (Fraden)

5.1.1 Sensor Classification

Sensors are classified based upon the kinds of the targeted signal domains or stimuli to be sensed as shown in table 5.1.

Stimulus	**Description**
Acoustic	Wave (amplitude, phase, polarisation), Spectrum, Wave velocity
Electric	Charge, Current, Potential, Voltage, Electric field, (amplitude, phase, polarisation and spectrum), Conductivity and Permittivity
Magnetic	Magnetic field (amplitude, phase, polarisation, spectrum), Magnetic flux and Permeability
Optical	Wave (amplitude, phase, polarisation, spectrum) Wave velocity, Refractive index, Emissivity, Reflectivity, Absorption
Thermal	Temperature, Flux, Specific heat, Thermal conductivity
Mechanical	Position (linear, angular), Acceleration, Force, Stress, Pressure, Strain, Mass, Density, Moment, Torque, Shape, Roughness, Orientation, Stiffness, Compliance, Crystallinity, Structural

Table 5.1 Different Stimuli for Sensors

5.2 Photoelectric Sensors

Photoelectric sensors are solid-state devices that detect either the presence or absence of light on the output transistor to change the output state of the sensor. As such they are suitable to operate control components such as relays and contactors. Photoelectric sensors are used to detect various materials at long ranges by non-contact sensing of a beam of light. Most photoelectric sensors use Light Emitting Diodes (LEDs) as a light source. LEDs can be built to emit green, blue, blue-green, yellow, red, or infrared light. The LED colours most commonly used in sensing are visible red and infrared. In applications that sense colour contrasts, the choice of LED colour can be important. Because LEDs are solid-state devices, they can last for the entire useful life of a sensor.

5.2.1 Operating Principles of Photoelectric Sensors

Photoelectric sensors utilises the physical properties of light sensitive materials. These types of sensors change their electrical features based upon the intensity of the light striking the receiver. Photoelectric sensing requires an emitter and receiver pair in order to operate. The sensor pairs operate by having a beam of light emitted at the right moment by the emitter which is then reflected back to the receiver by the object to be sensed.

The intensity of the light striking the receiver depends upon the presence or absence of the object to be detected (target). This change in intensity changes the electrical state of the receiver element. A variety of sensing "modes" exist, for the most part based on the emitter and receiver's physical orientation to each other.

5.2.2 Sensing Modes

Photoelectric sensors have an emitter element to generate a light beam, and a receiver element that receives the light beam. Photoelectric sensor pairs are designed to operate in one of three basic sensing modes: opposed, retro-reflective, or proximity. The proximity mode has distinct sub-modes.

5.2.2.1 Opposed Sensing Mode

A separate emitter and receiver are set up opposite each other, to establish a light beam between them. An object is detected when it passes between the emitter and receiver and blocks the emitter's light from reaching the receiver a shown in Figure 5.3. Opposed mode sensing is the most efficient sensing mode, and offers the highest level of sensing energy to overcome atmospheric contamination and sensor misalignment.

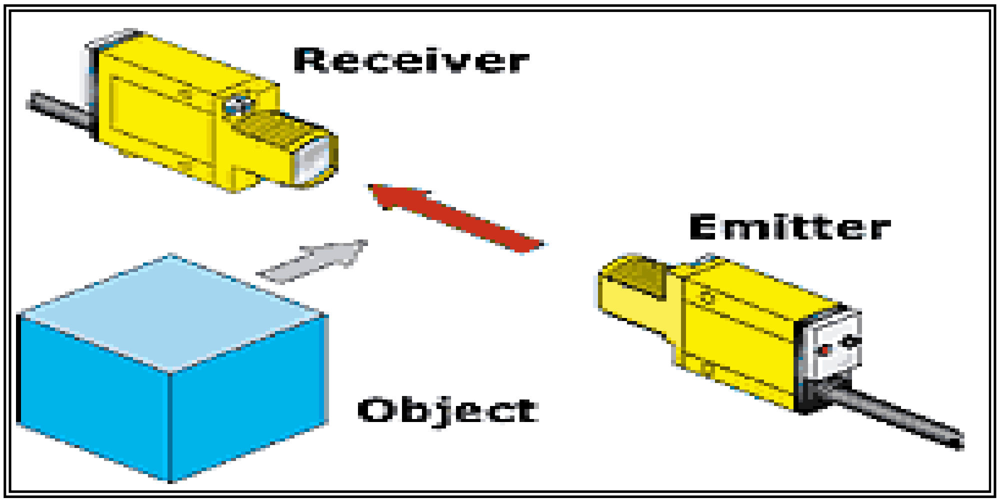


Figure 5.3 Opposed Sensing Mode (Banner Engineering, Minneapolis, MN)

5.2.2.2 Retro-reflective Sensing Mode

In the retro-reflective mode, the emitter and receiver are in the same housing. The sensor is set up so that the emitter's light beam strikes a reflective ("retro") target, and is directed back to the receiver. An object is sensed when it passes between the sensor and the target, interrupting the light beam, see Figure 5.4. This is the most popular sensing mode for conveyor applications where the objects are large boxes, cartons, etc.

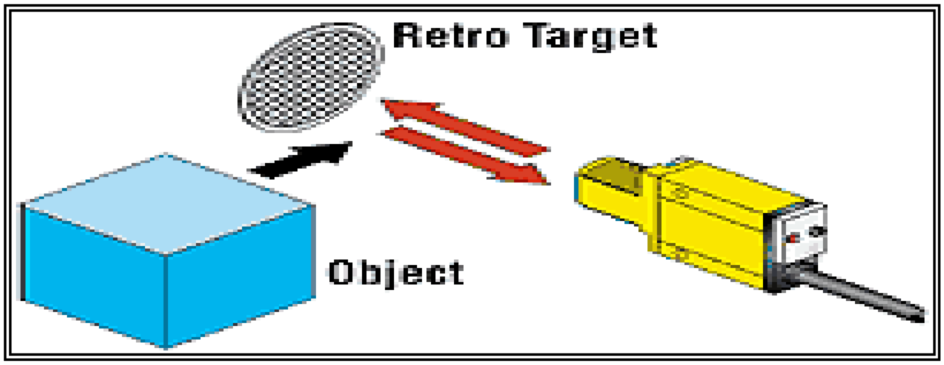


Figure 5.4 Retro-reflective Sensing Mode

5.2.2.3 Proximity Sensing Modes

In the proximity modes, the object is sensed when it passes in front of the sensor and reflects the emitted light back to the receiver, see Figure 5.5. The emitter and receiver are usually, but not always, in the same housing. The photoelectric proximity mode has five sub-modes: diffuse proximity, divergent-beam proximity, convergent-beam proximity, fixed-field proximity, and adjustable-field proximity. Depending upon the sub-mode used, these sensors can be the first choice for applications such as edge guiding or positioning of clear or translucent materials, sensing objects of low reflectivity, and colour mark sensing.

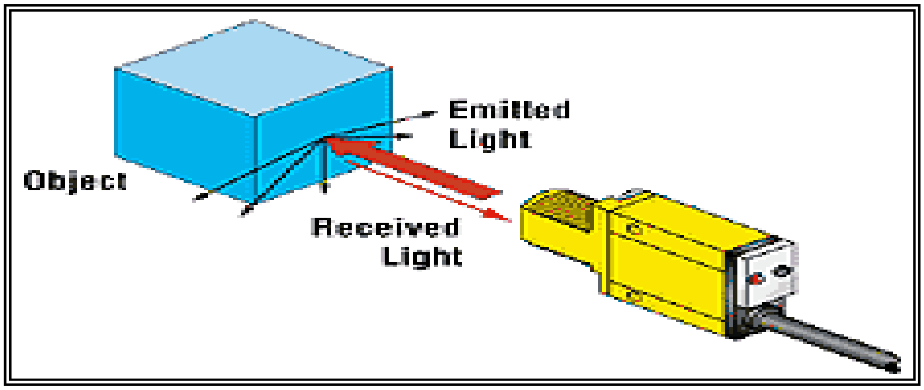


Figure 5.5 Proximity sensing mode

5.2.3 Ultrasonic sensors

Ultrasonic sensors operate in either the opposed or proximity sensing mode. The illustration in Figure 5.6 shows a proximity mode ultrasonic application, in which the sensor detects the reflection of its own sound waves from the surface being detected. In this application, the sensor is detecting the level of fill of a liquid in a container. The efficiency of ultrasonic sensing depends upon the reflectivity of materials to sound waves, and not light. Ultrasonic sensors can detect certain transparent materials and very dark-coloured materials that are difficult or even impossible to detect with photoelectric sensors.

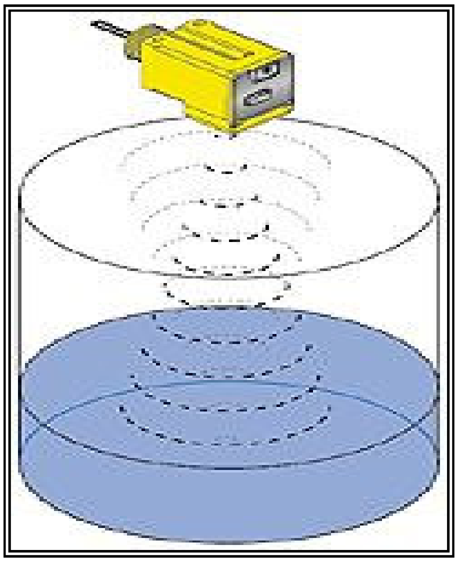


Figure 5.6 Ultrasonic sensing mode

5.3 Bar Code System

Bar codes are a technology for automatic identification which has found applications in many business sectors. A bar code is a self-contained message whose information is encoded in the geometry of its printed bars and spaces. In a simple bar code system, bar code reading is accomplished by passing a wand containing a light source and a photo-receptor across the code to be read. As the device passes over the pattern of bars and spaces, the photo-receptor receives a pattern of reflected light corresponding to the bars and spaces of the bar code. When a bar code is read, the patterns of light and dark contained in the bars and spaces are translated into patterns of ones and zeros which the reading computer interprets as numeric or alphanumeric data (Figure 5.7).

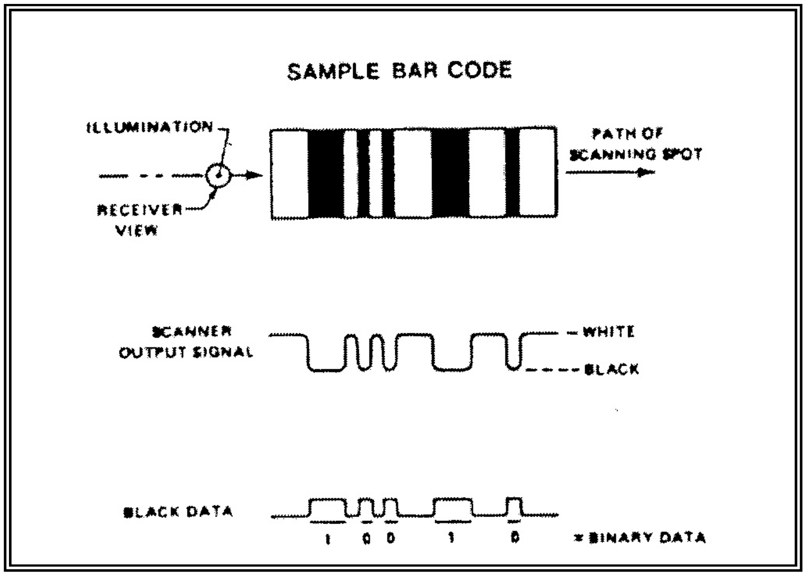


Figure 5.7 Operating Principle of a bar Code Reader

5.4 Bar Codes Scanners

Bar code scanners are electro-optical systems that include a means of illuminating the symbol and measuring reflected light. The light waveform data is converted from analogue to digital, in order to be processed by a decoder (which is either built into the scanner, or a separate plug-in device), and then transmitted to the computer-based application software. Scanners are either handheld or fixed-mount. Handheld scanners are used to read bar codes on stationary items. With fixed-mount scanners, items having a bar code are passed by the scanner - by hand as in retail scanning applications, or by conveyor belt in many industrial applications.

The moving beam scanners detect variations in contrast between the dark code marks and the light background colour of a label or carton surface. The laser spot traces through each bar and space in the code. In order to do so, the reader's sensor emits a beam of light directed towards the bar codes. The light from the wand reader is typically either visible or infrared, and the light from the guns is a low-powered laser beam. The black bars of the code reflect little of this light, while the spaces between the bars reflect most of it. A detector on the sensor notes how much of the beam is sent back to the reader (Figure 5.8).

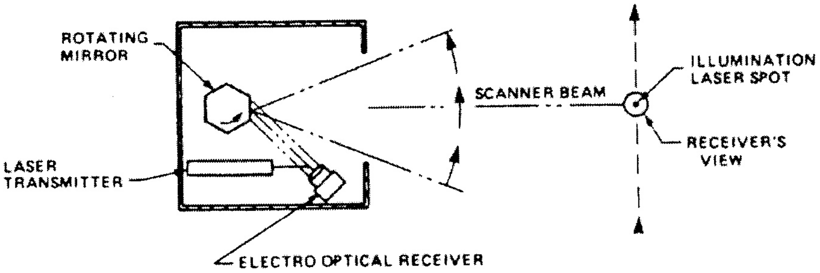


Figure 5.8 Working Principle of a Bar code Reader

5.5 Radio Frequency Identification (RFID)

Radio Frequency Identification is the technology that uses radio waves to identify people and objects. A basic RFID system consists of three components:

- An antenna or coil
- A transceiver (with decoder) and
- A transponder (RF tag) electronically programmed with unique information.

The antenna emits radio signals to activate the tag and read and write data to it. Antennas are the conduits between the tag and the transceiver, which controls the system's data acquisition and communication.

RFID tags are categorized as either active or passive. Active RFID tags are powered by an internal battery and are typically read/write, i.e., tag data can be rewritten and/or modified. An active tag's memory size varies according to application requirements; some systems operate with up to 1MB of memory. In a typical read/write RFID work-in-process system, a tag might give a machine a set of instructions, and the machine would then report its performance to the tag. This encoded data would then become part of the tagged part's history. The battery-supplied power of an active tag generally gives it a longer read range. The trade off is greater size, greater cost, and a limited operational life (which may yield a maximum of 10 years, depending upon operating temperatures and battery type).

Passive RFID tags operate without a separate external power source and obtain operating power generated from the reader. Passive tags are consequently much lighter than active tags, less expensive, and offer a virtually unlimited operational lifetime. The trade off is that they have shorter read ranges than active tags and require a higher-powered reader. Read-only tags are typically passive and are programmed with a unique set of data (usually 32 to 128 bits) that cannot be modified. Read-only tags most often operate as a license plate into a database, in the same way as linear barcodes reference a database containing modifiable product-specific information.

5.5.1 Areas of Application for RFID

Applications of RFID are in virtually every sector of industry, commerce and services where data is to be collected. The attributes of RFID are complimentary to other data capture technologies and thus able to satisfy particular application requirements that cannot be adequately accommodated by alternative technologies.

Principal areas of application for RFID that can be currently identified include:

- Transportation and logistics
- Manufacturing and Processing
- Security
- Animal tagging
- Waste management
- Time and attendance
- Postal tracking
- Airline baggage reconciliation

A number of factors influence the suitability of RFID for given applications. The application needs must be carefully determined and examined with respect to the attributes that RFID as well as other data collection technologies can offer. Where RFID is identified as a contender further considerations have to be made in respect to application environment, electromagnetics, standards, and legislation concerning use of frequencies as well as power levels.

5.6 Multi-Sensor Data Fusion

Multi-sensor data fusion is the technology concerned with addressing the problem of combining data and information from various sensors. The intention is to achieve improved accuracies and better inference about the environment, using multiple sensors than could be achieved by the use of a single sensor alone (Durrant-Whyte). The concept of multi-sensor data fusion is not new. Human beings and animals have evolved the capability to use multiple senses to improve their ability to survive. The human or animal brain is a good example of a data fusion system. The brain integrates a variety of sensory information such as sight, sound, smell, taste, and touch data to achieve more accurate assessment of the surrounding environment and identification of threats, thereby improving their chances of survival.

Most often a sensory system cannot rely on a single sensor to provide sufficient information as sensor measurements contain noise and can be *erroneous.* Measurements of a single sensor can be *incomplete* and thus different types of sensors can measure different properties of the surrounding. It is therefore necessary to employ multiple sensor in order to understand the environment.

Sensor fusion algorithms can be classified into three different groups;

- First, fusion based on probabilistic models such as Bayesian reasoning, evidence theory, robust statistics, recursive operators;
- Second, fusion based on least-squares techniques such as Kalman filtering, optimal theory, regularisation and uncertainty ellipsoids and;
- Thirdly, intelligent fusion such as fuzzy logic, neural networks and genetic algorithms.

The process of sensor fusion can be functionally represented by three tasks: data alignment, data association, and data fusion. Inherent in all aspects of the fusion process is the use of models describing the sensors and the systems as well as the environment in which they operate.

The first task, data alignment, entails the incorporation of all available sensor data and their transformation into a common spatial and temporal reference frame. The second task, data association, involves the validation or rejection of the sensor data with the use of gating which is performed by verifying that the measurement lies within a region predicted by the model. Finally the third task, data fusion, combines the validated measurements using a weighted average or least-squares estimation method to provide an estimate of the signal with a lower variance. A summary of the sensor fusion process is given in Figure 5.9.

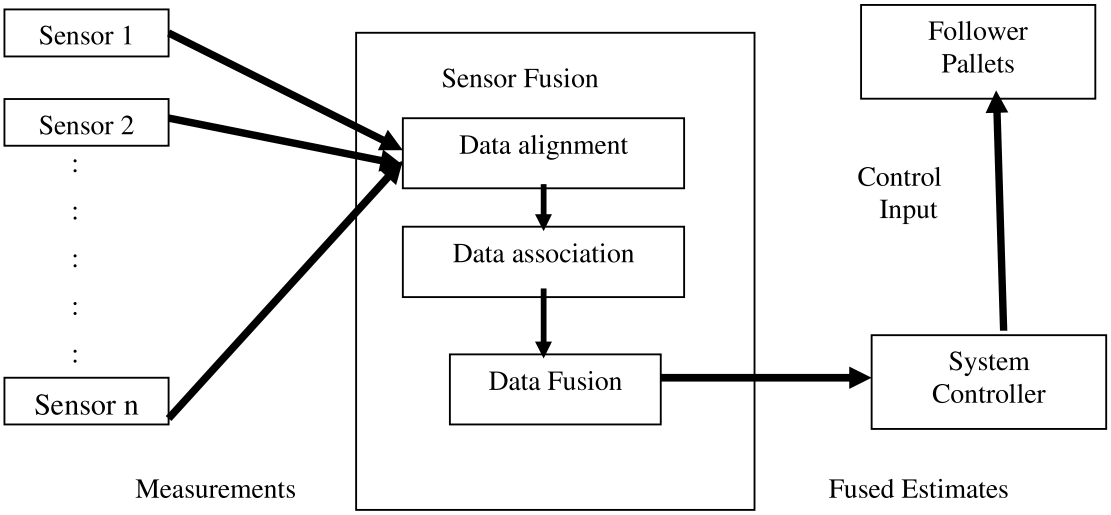


Figure 5.9 Sensor fusion process

5.7 Simulation and Modelling

Computer simulation is a technique that allows building of and experimenting with a model of a real system on a computer. Although there are several different types of simulation, the focus of this project is on discrete-event simulation as applied to manufacturing systems. The discrete-event simulation technique is used for systems where the state changes occur when events happen at discrete points in time. System modelling is an important component of engineering in that a model represents a system and the relationships that influence that system. This representation can take the form of physical and analogue models, such as globes or clay models, or schematic and mathematical models, such as organizational charts and equations.

In general, models are used to save time and money, for training purposes, to determine how to optimise a system, to predict performance, to enhance understanding of system behaviour as well as to examine worst-case scenarios.

5.7.1 When is Simulation the Appropriate Tool?

Many authors have discussed circumstances under which simulation is the appropriate tool to use (Gullander). Simulation can be used for the following purposes:

- Simulation enables the study of, and experimentation with, the internal interactions of a complex system, or of a subsystem within a complex system.
- Informational, organisational and environmental changes can be simulated and the effect of these alterations on the model's behaviour can be observed.
- The knowledge gained in designing a simulation model may be of great value toward suggesting improvement in the system under investigation.
- Changing simulation inputs and observing the resulting outputs may obtain valuable insight obtained into which variables are most important and how variables interact.
- Simulation can be used as a pedagogical device to reinforce analytic solution methodologies.
- Simulation can be used to experiment with new designs or policies prior to implementation, so as to prepare for what may happen.
- Simulation can be used to verify analytic solution.

5.7.2 Systems and System Environment

To model a system, it is necessary to understand the concept of a system and the system boundary. A system is defined as a group of objects that are joined together in some regular interaction or interdependence toward the accomplishment of some purpose. An example is a production system manufacturing automobiles. The machines, component parts, and workers operate jointly along an assembly line to produce a high-quality vehicle.

A system is often affected by changes occurring outside the system. Such changes are said to occur in the system environment. In modelling systems, it is necessary to decide on the boundary between the system and its environment.

5.8 Simulation of Shop-floor Control Systems

The close relationship between a manufacturing system and its shop-floor control system is evident: the functions and behaviour of the control system strongly affect the flow of parts and material. Therefore, analysing the parts flow without fully considering the control system can result in wrong conclusions. Concurrent simulation of the information flow in the shop-floor control system and the physical systems material flow, makes it possible to evaluate not only the chosen layout, resources, etc., but also the control system and its behaviour. Traditionally, discrete-event simulation has been used mainly for analysing the flow of parts and material on the shop floor. However, many discrete-event simulators can be used also for information flow simulation and analysis, making it possible to model and simulate the information flow in shop-floor control systems. The simulated control systems can control (i) model of the manufacturing facility in either a discrete-event or a geometric simulator, (ii) the real-world facility, (iii) or a combination of simulated and real worlds. In this way the accuracy of the simulation analysis and the visibility of the simulation are increased. Some software vendors offer interfaces that make it possible to directly integrate discrete-event and geometric simulators. When combining both types of simulators, the control logic for the specific equipment can be simulated in the geometric simulator, while supervisory controllers are simulated in the discrete-event simulator. The integration between the two types of simulators opens up a new perspective for simulating all aspects of a virtual factory. Improved integration of the two types of analysis has the potential of increasing quality since simulation input data can become more accurate. Another important issue for simulation and shop-floor control is the link to the real shop floor. The virtual factory model need not serve only as a stand-alone simulator; it can also be an integral part of the factory system.

5.9 Simulation software tools

The development of simulation software tools is rapid at this time, due to increased interest in simulation by manufacturing companies. An overview of simulation tools for manufacturing systems can therefore show the software status at the present time. There is a need to get an overview of what simulation in manufacturing can offer and to identify where research and development efforts are needed most.

Table 5.4 Discrete event and geometric simulation software tools and their vendors.

Name of Simulation Software	Vendors
Arena	Systems Modelling Corporation
CimStation	SILMA
AutoMod	**AutoMod X**
GRASP	BYG Systems Ltd
DE3	BYG Systems Ltd
IGrip	Deneb Robotics
Extend	Imagine That, Inc
Robcad	Tecnomatics Technologies Inc
Factor/Aim	Pritsker Corporation
Workspace 5	Robot Simulations Ltd
Micro Saint	Micro Analysis and Design, Inc
ProModel	Production Modeling Corp. of Utah
Quest	Deneb Robotics
Simple++	Aesop
Taylor II	F & H Simulations Inc
DE3	BYG Systems Ltd
Witness	Lanner Group Inc

5.9.1 Overview Features

There are some overview features to be considered, before investing in simulation software, that are common to both types of simulation tools. These common features are:

- Manufacturing application indicating the possible application areas (in manufacturing) of the software, e.g. material handling or 3-D visualization.

- Hardware platform that are supported by the software, e.g. Workstation, PC or Macintosh

- The platform supported by the software, e.g. Unix or Windows

- User interface: points out what type of environment that the user faces, e.g. menu bars, dialog boxes, 2-D or 3-D animation.

- Integration interface showing what kind of interfaces the software offers for easy data transfer, e.g. simple data (ASCII), database data or CAD-file transfer.

- Programming language used e.g. adding if-then-else logic to a simulation.

- Shop-floor integration and interface to the real shop-floor, e.g. robot controller

- Reporting possibilities and documentation of the simulations e.g. output statistics or recorded animation.

5.10 Chapter Summary

In this chapter a theoretical perspectives of the technologies involved in the design of the MSS apparatus was provided. The various types of sensory systems, scanner and bar coding systems were discussed. An overview of simulation and modelling techniques and tools used in manufacturing systems were articulated as well as aspects of multi sensor data fusion techniques.

Chapter 6

5 ACTUATION OF THE MSS APPARATUS

6.1 Introduction

This chapter discusses the design of the power electronics drive modules used to control the stepper and DC servomotors in order to facilitate the operation of the MSS apparatus to effect pallet movement and manipulation within the conveyor system implementing synergistic design approach. The discussion also reviews the different motor types used in industry as well as electronic methodologies used to control and drive various motors.

6.2 The Mechatronic Sensory System Apparatus

The Mechatronic Sensory System (MSS) has been developed as a computer based technology in order to enable ease integration into the CIM environment. The MSS apparatus has to control certain specific system motions through the computer based controller and there is involvement of motion and action of some sort in its operation. Actuators are devices that can transform one form of energy into another (Histand et al). As the power capabilities of the standard computer inputs/outputs (I/O) ports are far lower than the power required to actuate the loads on the MSS, it was necessary to design certain driver power modules for driving actuators.

The mechanism was designed to be driven rotationally or linearly and thus actuators were found necessary to be implemented to convert electrical energy into rotational/linearly mechanical energy. Different mechanisms of the MSS apparatus were used to position pallets and control the operation of the conveyor belt system. Thus actuators should be able to be controlled on a start/stop motion at certain desired points along the conveyor system.

6.3 Stepper motors

Stepper motors are electromechanical motion devices used primarily to convert information in digital form to mechanical motion. Stepper motors operate by rotating in steps. The rotor consists of several permanent magnets of both north and south polarity. The stator comprises a series of electro-magnets that can be individually switched on or off. When a stator electro-magnet is switched on, the rotor experiences a torque which tends to align it to the activated stator coil. The only movement that takes place is the rotor rotating just enough to align itself with the stator coil. No further movement occurs, as there is zero net torque acting on the rotor. In order to cause the rotor to rotate any further, the stator coil to which the rotor is aligned must be switched off and another coil must be activated. The motor will then experience a torque to align itself with the latest activated coil (Figure 6.1). The larger the number of rotor poles and the coils are, the smaller the step size.

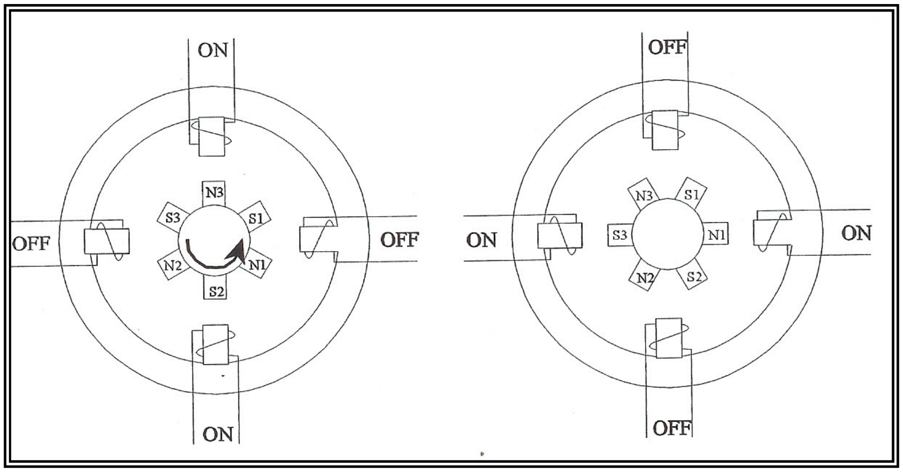


Figure 6.1 Operation Principles of a Stepper Motor

In order to maintain continuous rotation, the stepper motor must be supplied with a series of pulses that activate the stator coils in a sequence that facilitates the continuous rotation. If the stepper motor is to be controlled by a computer, an indexer and a dedicated stepper motor driver card will be needed. The indexer converts computer signals into pulses for the driver card to interpret. The driver card converts these low powered clock pulses to high-powered sequence pulses that drive the stepper motor. Stepper motors can be divided into two main categories according to the rotor configurations: permanent magnet and variable-reluctance stepping motors.

6.3.1 Permanent-Magnet Stepping Motors

The operating principle of a permanent-magnet stepping motor can be illustrated by means of a cross section as shown in Figure 6.2, where a rotor is magnetised to consist of four permanent-magnet poles and a stator contains two phase windings that can be excited with either polarity currents. Each phase winding produces the same number of poles as the rotor. The magnetic poles produced by the stator currents cause the rotor to move as shown in Figure 6.2, for the excitation sequence i_A+, i_B+,i i_A-, i_B-, i_A+, …… By tracking the movement of the point *P* on the rotor, it can be shown that the step-angle for the motor shown is 45°. The electromagnetic torque T_{em} is produced by the interaction of the stator and rotor magnetic fields. T_{em} is proportional to the phase current and a function of the small deviation in θ from its equilibrium position.

The permanent-magnet motors suffer from the disadvantage of higher inertia-torque ration and the difficulty in manufacturing motors with a fairly small step-angle. Permanent-magnet step motors have the advantage that there is some torque to maintain position, in case the drive fails.

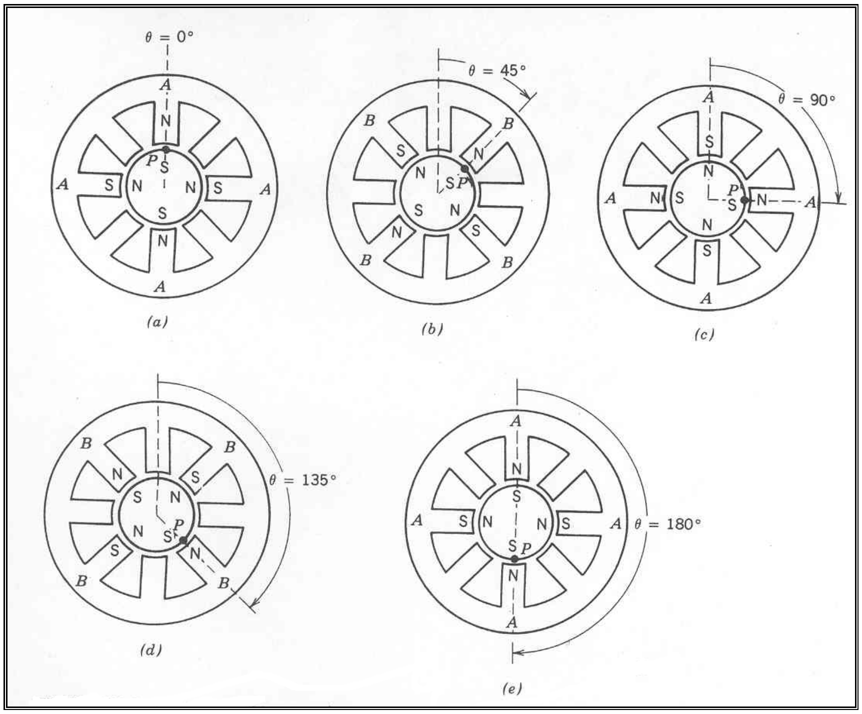


Figure 6.2 Two-phase Permanent Magnet Stepper Motor

6.2.2 Variable-Reluctance Stepping Motors

Variable-reluctance stepping motors use a ferromagnetic rotor in its operation. The stator windings are excited in a sequence that will cause the rotor to move to a position that minimizes the magnetic reluctance between the stator and rotor (ref Figure 6.3). This is accomplished by using a different number of rotor teeth and stator poles. For any given set of stator poles windings that are excited, only a certain set of the rotor poles will line up. When the next set of pole windings is excited, a different set of rotor poles will have to line up, causing the rotor to move one step.

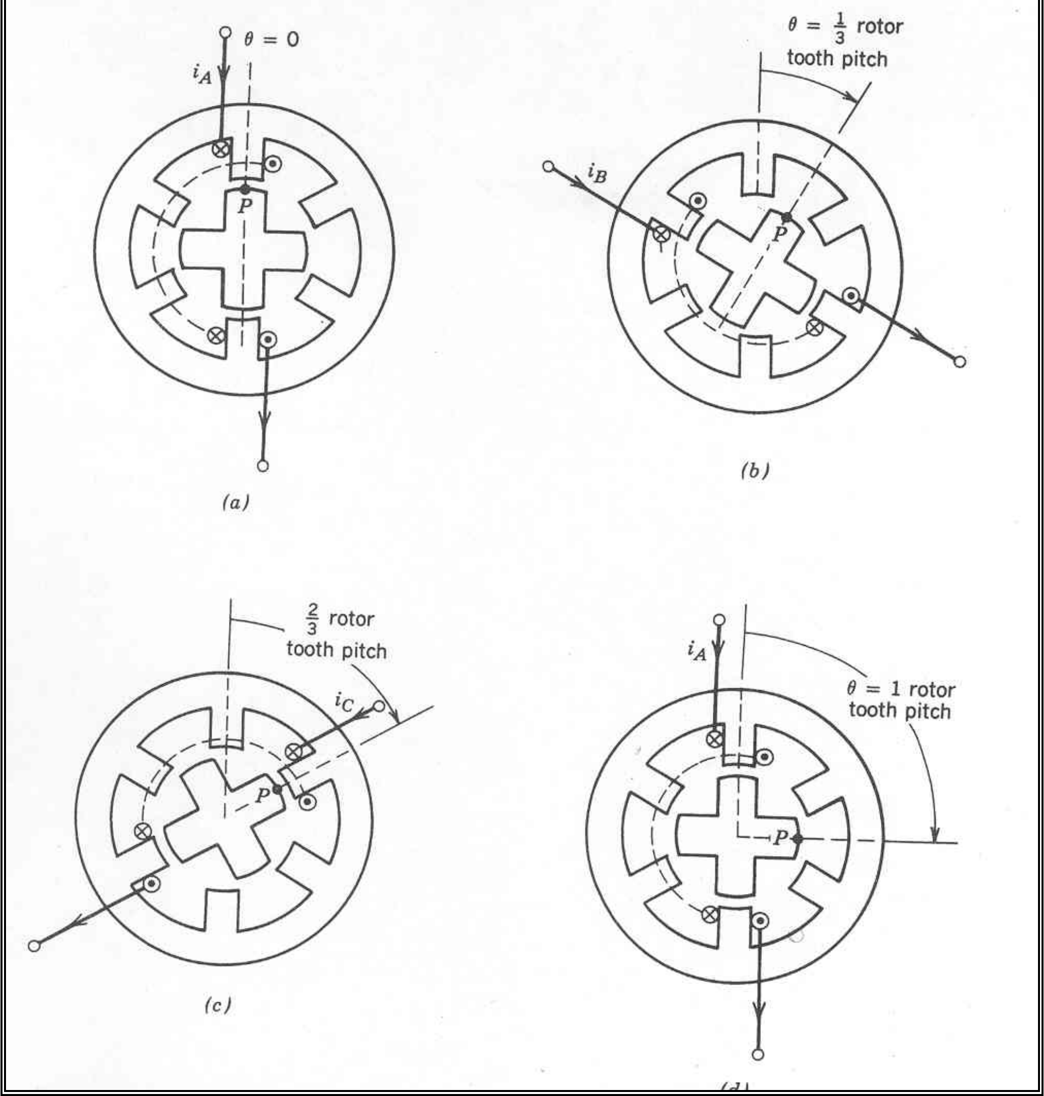


Figure 6.3 One Step Operation of a Variable Reluctance Steeper Motor (6 Stator Poles and 4 Rotors).

The stepper motors offer the following advantages to the MSS apparatus:

- Precise movement control can be obtained as position error is non cumulative and thus a high accuracy of motion control is possible even under open loop control environment. This reduces the overall system cost.
- Stepper motors are easily adaptable to digital control applications due to the incremental nature of their commands and motions.
- Torque capacity and power requirements can be optimised and electronic switching can control the response.
- By using a calibrated gear system that converts the stepper motor's rotary motion into linear motion, the MSS apparatus's movement accuracy can be controlled to almost any degree.

However the following disadvantages of stepper motors made them unsuitable to implement in the MSS apparatus:

- Specialised electronic control circuits that would have to be used to power the motor.
- Low torque capacity compared to DC motors
- Large vibration levels due to stepwise motion
- Limited operational speed (due to torque capacity and pulse-missing problems of switching systems and drive circuits)
- Large errors and oscillations could result when a pulse is missed under open loop control.
- Stepper motors were larger and more expensive than DC servomotors of similar power capacity.

6.4 Direct Current (DC) Motors

This section summaries the works of (Auslander et. al), (Standler) and (Kuo) on the development of DC servomotors and reviews the fundamental operational concepts of the DC Motor and its control of the MSS apparatus.

6.4.1 Operating Principles of DC Motors

The DC servomotor is basically a torque transducer that operates in a linear relationship (Kuo et al.). It utilizes a principle that when a current in a conductor is moved through a magnetic field, a force is produced in a direction perpendicular to the current and magnetic field direction (Young).

The current carrying conductor of a DC motor comprises of a rotor and a rotating shaft is directly proportional to the field flux and the armature current. The DC motor (Figure 6.4) comprises a stationary outer housing called the stator that supports the radial magnetized poles. The poles consist of either permanent magnets or field coils. The rotor consists of a rotating shaft supported by bearings, an iron core into which windings are anchored and a commuter to deliver current and control its direction in the rotor windings. Brushed (Figure 6.5) motors consist of spring-loaded brushes to ensure continual contact with the moving commutator conducting segments. There is an air gap between the rotor and the stator where the magnetic fields interact.

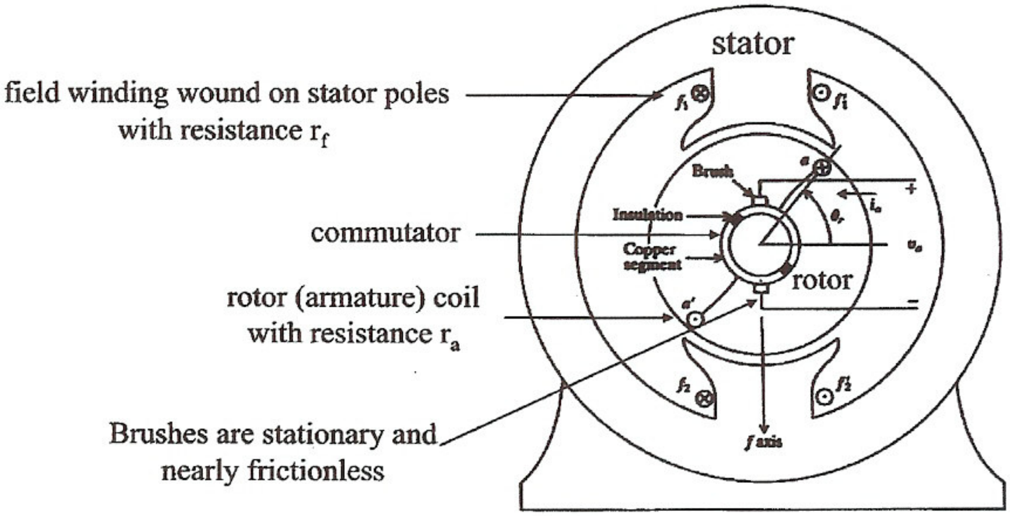


Figure 6.4 Operating Principles of a DC Motor

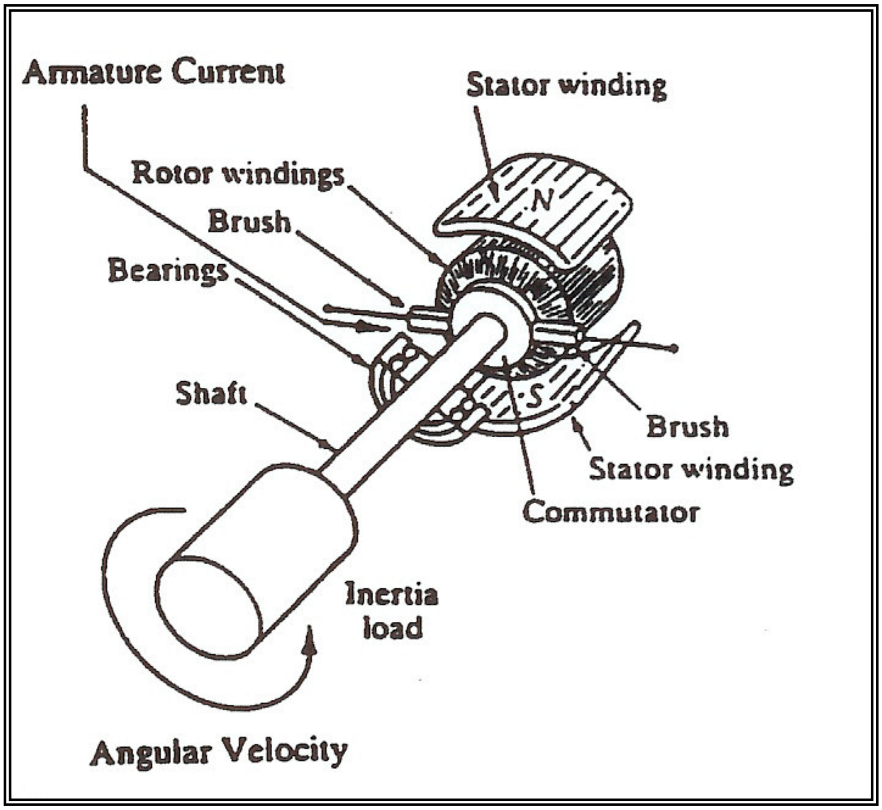


Figure 6.5 Schematic Drawing of a Brushed DC Motor

The torque developed on the motor shaft is directly proportional to the field flux and the armature current. If a current-carrying conductor is established in a magnetic field with flux, and the conductor is located at a distance r from the centre of rotation, then the relationship between the developed torque, magnetic flux, and armature current, I_a is

$$T = K\phi I \tag{6.2.1}$$

Where T is the shaft torque (Nm), ϕ is the magnetic flux (webers), I is the armature current (amperes), and K is a proportional constant.

When the conductor moves in the magnetic field, a voltage is generated across its terminals. This voltage, which is proportional to the shaft velocity, tends to oppose the current flow.

The relationship between this back emf and the shaft velocity is

$$E=K\,\phi\,\omega \qquad (6.2.2)$$

Where, E denotes the back emf (volts), ω and is the shaft velocity (rad/sec) of the motor. Equations (6.2.1) and (6.2.2) form the basis of DC servomotor operation. At this point, a linear differential equation for the DC motor's electrical circuit can be written by using *Kirchoff's Voltage Law*, the law states that the sum of all voltages in the circuit must equal to zero. For the DC motor, this can be written as:

$$V_a - R_i - L\frac{di}{dt} = 0 \qquad (6.2.3)$$

In deriving the equation of motion for the motor, the friction on the shaft of the motor is approximated as a linear function of the shaft velocity. The approximation that the friction on the shaft of the motor k_f, is a linear function of the shaft velocity is made. Newton's Law of Motion states that the sum of all torques produced on the shaft is linearly related to the acceleration of the shaft by the inertial load of armature $\boldsymbol{I_R}$. The preceding statement can be written as:

$$\sum m = \tau_m - k_f\omega - \tau_a = I_R\omega \qquad (6.2.4)$$

Substituting equation (6.2.1) and (6.2.2) into equations (6.2.3) and (6.2.4), and rearranging in terms of the time derivatives, leads to the following two fundamental equations which governs the motion of the motor. Both

$$\frac{di}{dt} = \frac{R}{L}i + \frac{k_e}{L}\omega + \frac{V_a}{L} \qquad (6.2.5)$$

$$\frac{dw}{dt} = \frac{k_m}{I_R}i + \frac{-k_e}{I_R}\omega - \frac{\tau_a}{I_R} \qquad (6.2.6)$$

Both equations are linear functions of current and velocity and they include the first order time derivatives. A simplified DC motor model is sufficient for the MSS apparatus case. For that reason, the motor inductance and motor frictions are considered negligible and are approximated as zero.

Hence, equations (6.2.5) and (6.2.5) can be approximated as

$$i = -\frac{k_e}{R}\omega + \frac{1}{R}V_a \qquad (6.2.7)$$

$$\frac{d\omega}{dt} = \frac{k_m}{I_R}i - \frac{\tau_a}{I_R} \qquad (6.2.8)$$

By substituting equation (6.2.7) into equation (6.2.8), an approximation model for the DC motor which is only a function of the current motor speed, applied voltage and applied torque is obtainable. Since the motor inductance is neglected, the current through the windings is not considered in the equation of motion of the motor. The current will then reach a constant state immediately as compared to the velocity of the shaft, which takes time to speed up from some initial speed to a final speed after a change in the input voltage. The motor's dynamics can be represented with a state space model, it is a system of first order differential equations with parameters position, θ, and velocity, ω , that uniquely represents the its operation. The inputs to the motor is then the applied voltage and applied torque.

An arrangement of commutator segments and brushes ensures that the current always flows in the same direction relative to the magnetic field. This results in a constant torque in the direction relative to the magnetic field. The main difference among the various types of DC servomotors lie in the method employed to develop the magnetic field (the type of excitation). Permanent magnet DC servomotors use, as the name suggests, permanent magnets to develop the magnetic field. Before permanent-magnet technology was fully developed, the torque per unit volume or weight of a DC servomotor with a permanent-magnet (PM) field was far from desirable. Today, with the development of the rare-earth magnet, it is possible to achieve very high torque-to-volume PM DC servomotors.

DC servomotors with low inertia have very high torque-to-inertia ratios, and the low-time-constant properties. Such DC servomotors can be easily controlled with respect to speed and position. DC servomotors were implemented in the MSS apparatus because of the following advantages:

- Torque delivery would be independent of the rotor position.
- An increase in load that slowed down the rotor would cause the motor to draw more current, increasing the torque output. Also, the increase in current flow can be used to detect a load increase and initiate corrective action to prevent any damage to the motor.
- The motor's speed could easily be controlled by using appropriate speed control circuitry
- Feedback control gave much faster response time.

However, the following were disadvantages of using the DC servomotor are:

- Armature of the DC servomotor rotated slowly and thus movements in small increments are not possible without the use of expensive and accurate reduction gears.
- It was almost impossible to stop the armature at a specified position while maintaining acceptable speed response. An encoder or position sensor will have to be used in closed-loop.
- Torque delivery decreased with increasing speed. Thus, little torque was delivered at high speeds.

6.5 Basic Classification of DC servomotors

DC servomotors can be classified into several broad categories based on the way the magnetic field is produced, and on the basic design and construction of the armature. In terms of the magnetic field, DC servomotors can be classified as *variable magnetic flux* motors and the *constant magnetic flux* motors.

6.5.1 Variable Magnetic Flux DC servomotors

In *variable magnetic flux* motors, the magnetic field is produced by field windings that are connected to external sources. These motors can also be divided into four subclasses:

- The separately excited-field motor, in which the field windings is separate from the armature as shown in Figure 6.6 (a).
- The series-field motor, in which the field winding is connected in series with the armature as shown in Figure 6.6 (b).
- The shunt-field motor, in which the field winding is connected in parallel to the armature as shown in Figure 6.6 (c).
- And the compound motor, which is a combination of a series-filed and a shunt-field motor as shown in Figure 6.6 (d).

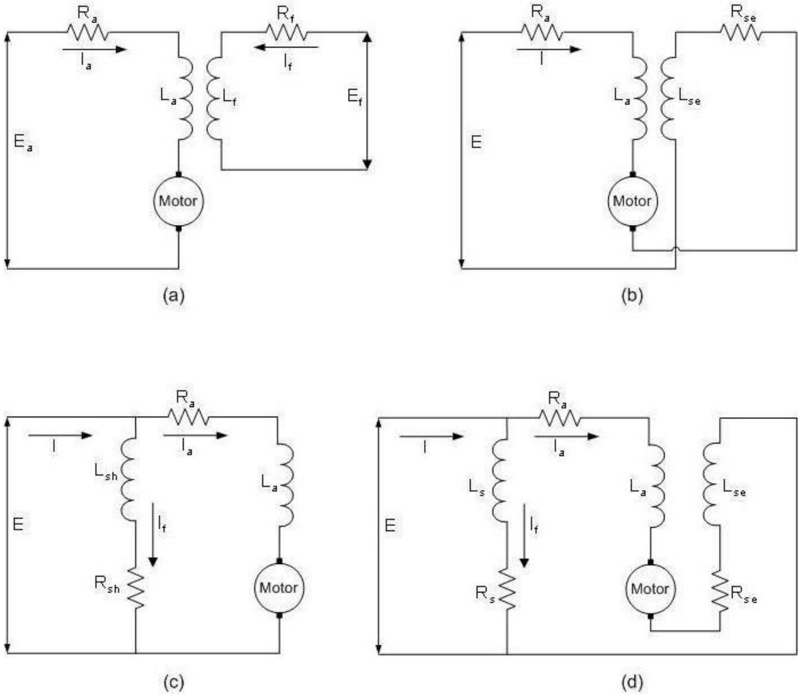


Figure 6.6 DC Motor Configuration (a) Separately Excited (b) Series DC (c) Shunt and (d) Compound

For the series-field type, since the magnetic flux in the motor is proportional to the varying field current, there is a relationship between the torque and speed that is generally non-linear. Thus, series-field-type DC servomotors are useful only for specific applications where high torque at low speeds is required.

Equation of the back emf produced in the rotor windings is

$$E = E_b = K_m \phi \omega_a \quad (6.2.3),$$

$$\text{and, } T_m = K_m \phi I_a = K I_a^2 \quad (6.2.4),$$

$$\text{thus, } Tm = E^2 / K_a \omega_a^2 \quad (6.2.4).$$

The series DC motor torque usually drops off rapidly as the motor speed increases
(see Figure 6.7).

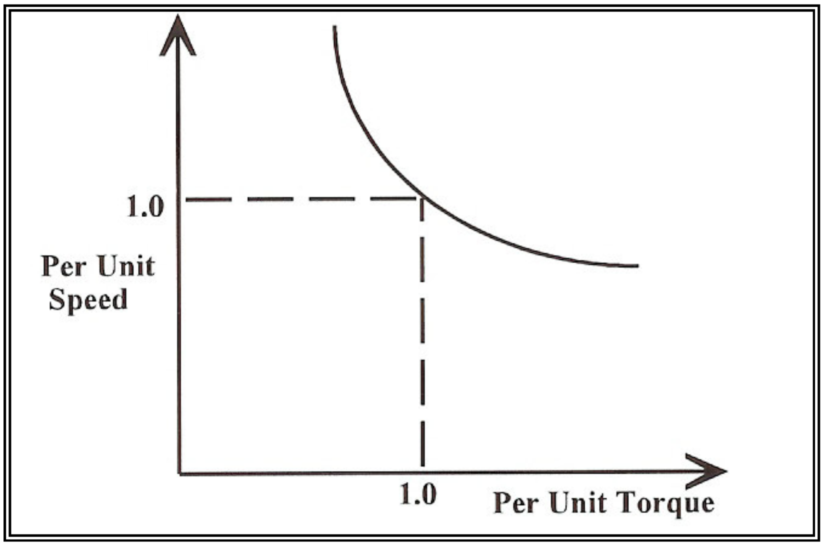


Figure 6.7 Speed-Torque Characteristics of a Series DC Motor

For separately excited DC servomotor, since the magnetic flux is independent of the armature current, it can be controlled externally over a wide range (refer Figure 6.8). Under steady-state conditions and considering equations 6.2.3 and 6.2.4:

$$E = K_m \phi \omega + R_a I_a \qquad (6.2.5),$$

$$\text{thus, } Tm = K_m \phi (E - K_m \phi \omega_a / R_a \qquad (6.2.6).$$

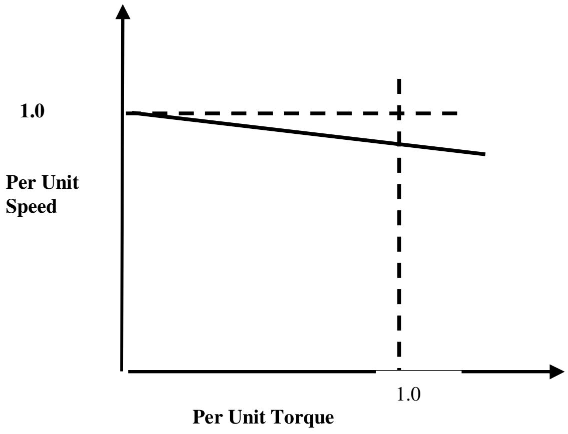


Figure 6.8 Speed – Torque Characteristics of a Separately Excited DC Motor

A DC shunt motor is essentially a constant speed machine with a low speed regulation (refer Figure 6.9). Its speed in inversely proportional and thus can be controlled by regulating the field flux.

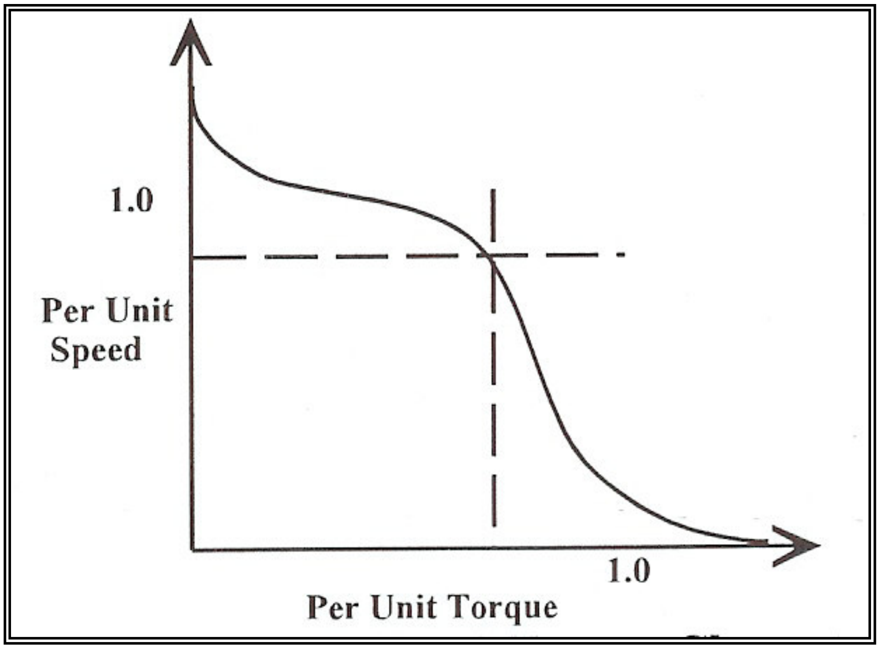


Figure 6.9 Speed– Torque Characteristics of a Compound Excited DC Motor

A compound DC servomotor combines the speed-torque characteristic of series-field motor and a shunt-field motor, as shown in Figure 6.10.

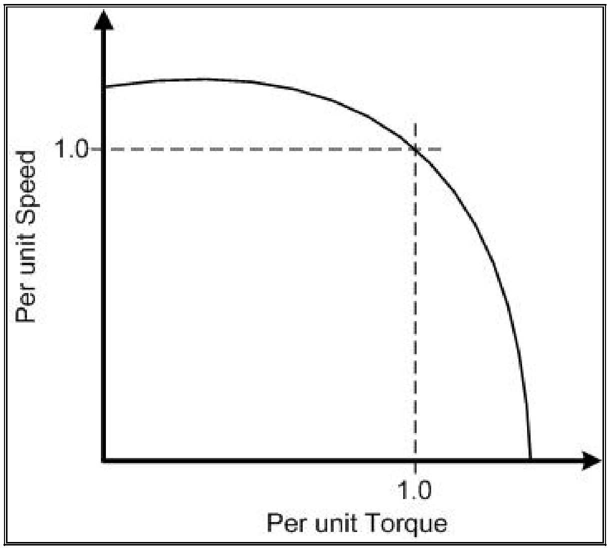


Figure 6.10 Speed- Torque Characteristics of a Shunt DC Motor

6.5.2 Constant Magnetic Flux DC servomotors

The constant-magnetic-flux DC servomotor is also known as the permanent magnet (PM) DC servomotor (ref Figure 6.11). In this case, a constant magnetic field is produced by a permanent magnet. This allows the torque-speed characteristics of the motor to be relatively linear (ref Figure 6.8). PM DC servomotors were implemented in the MSS apparatus.

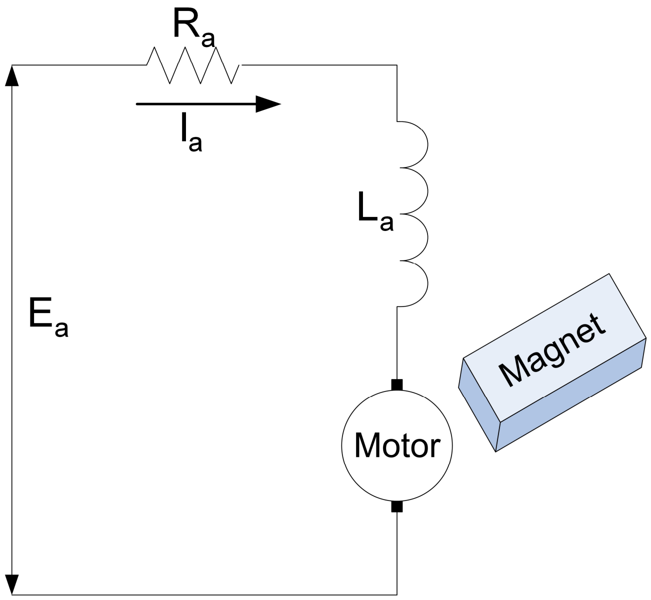


Figure 6.11 Schematic Diagram of a Permanent Magnet DC Motor

The equations that describe the operation of a permanent magnet DC motor is identical to those of a shunt connected DC motor with the field current held constant. For the PM DC servomotors, k_v is included in the equation as constant determined by the strength of the magnet, reluctance of the iron, and the number of turns of the armature windings. The time-domain block diagram may be developed using the following equations:

$$V_a = r_a[1+ \tau_a D]\ i_a + \omega_r \quad k_v \qquad (6.2.7).$$

$$Te\ - T_L=(B_m+JD) \qquad (6.2.8)$$

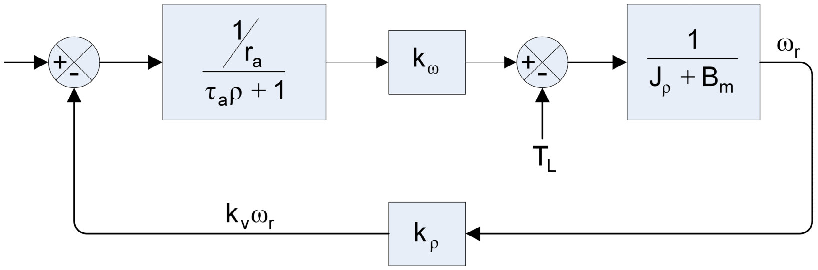


Figure 6.12 Time-Domain Block Diagram of a PM DC Motor

PM DC servomotors can be further classified according to commutation scheme and armature design. Conventional DC servomotors have mechanical brushes and commutators, while the brushless DC servomotors have the commutation done electronically. According to the armature construction, the PM DC servomotor can be broken down into three types of armature design: iron core, surface wound, and moving-coil motors.

6.5.3 Iron-Core PM DC servomotors

The rotor and stator configuration of an iron-core PM DC servomotor is shown in Figure 6.13. The permanent magnetic material can be barium ferrite, Alnico, or rare earth compound. The magnetic flux produced by the permanent magnetic passes through a laminated rotor structure that contains slots the armature conductors are placed in the rotor slots. This type of DC servomotor is characterised by relatively high rotor inertia, high inductance, low cost, and reliability.

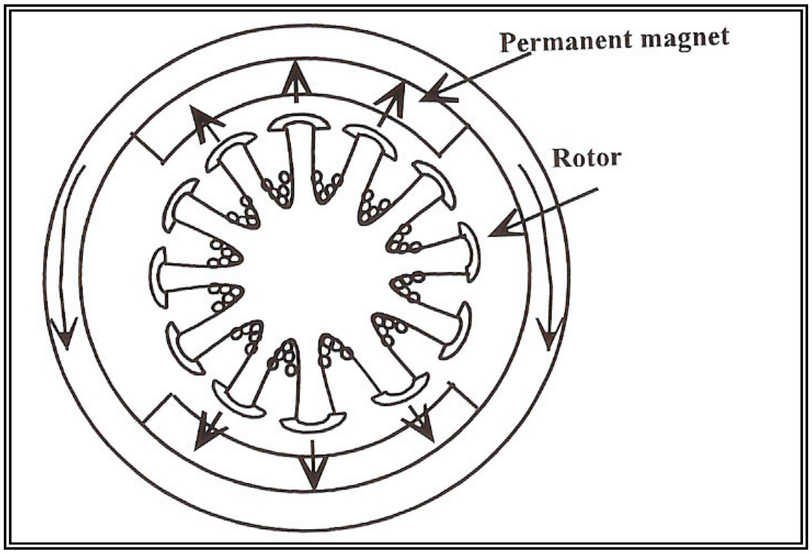


Figure 6.13 Cross-sectional view of a PM Iron Core DC Motor

Figure 6.14 shows the rotor construction of a surface-wound PM DC servomotor. The armature conductors are bonded to the surface of a cylindrical rotor structure, which is made of laminated discs fastened to the motor shaft. Since no slots are used on the rotor on this design, the armature has no "cogging" effect. Since the conductors are out in the air gap between the rotor discs and the permanent magnet field, this type of motor has lower inductance than that of the iron structure. Due to the air gap between the magnet and the low-inductance rotor being larger than in the iron-core motor, a larger magnet is required in order to provide a magnetic flux equivalent to that of the iron-core motor. Therefore, surface-wound DC servomotors are more expensive to produce and have larger outside diameters than equivalent iron-core motors.

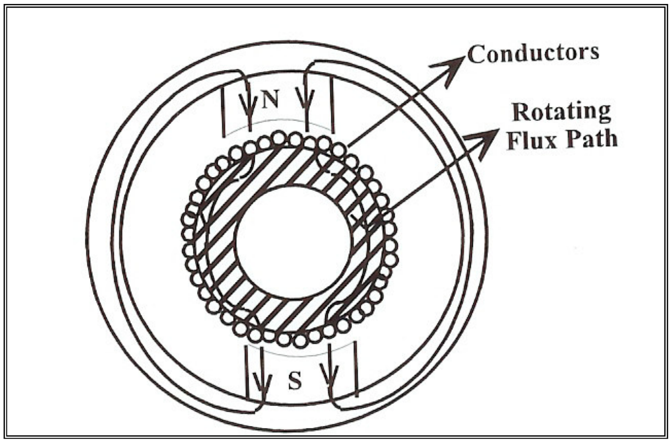


Figure 6.14 Cross-sectional view of a PM Surface Wound DC Motor

6.5.4 Moving-Coil DC servomotors

Moving-coil motors are design to have very small moments of inertia and very low armature inductance. This is achieved by placing the armature conductors in the air gap between a stationary flux return path and the permanent magnet structure, as shown in Figure 6.15. In the case of Figure 6.16, the conductor structure is supported by nonmagnetic material, usually epoxy resins and fibreglass-to form a hollow cylinder. One end of the cylinder forms a hub, which is attached to the motor shaft. Since all unnecessary elements have been removed from the armature of the moving-coil motor, its moment of inertia is very low. However, it has a larger air gap than the two motors discussed earlier, and therefore requires an even larger magnetic structure than do the other two types of motors to produce an equivalent air-gap flux. The low-inertia and low-inductance properties make the moving-coil motor the best actuator choice for high-performance control systems.

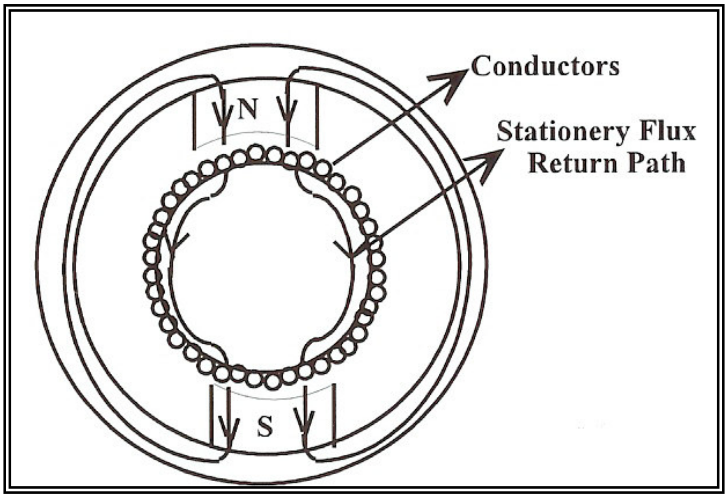


Figure 6.15 Cross-sectional view of a PM Moving Coil DC Motor

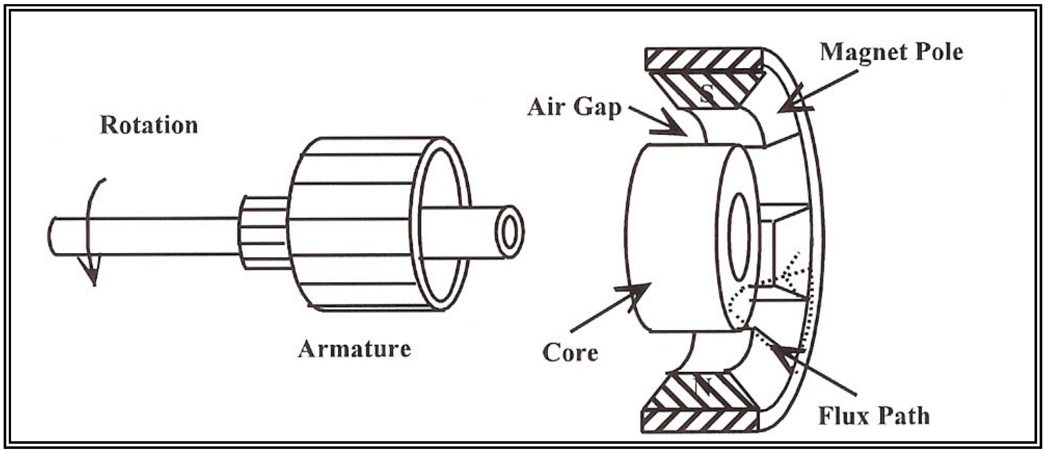


Figure 6.16 Exploded side view of a PM Moving Coil DC Motor

6.6 The DC Motor Control

DC motor can be operated over a wide range of speeds and torque and are particularly suited for variable drive actuators. The function of a conventional servo system that uses a DC motor as the actuator is almost exclusively motion control (position and speed control). There are applications that require torque control and utilize sophisticated control techniques. There are two methods normally used to control a DC motor: the armature control and the field control.

6.6.1 The armature Control

Here the field current in the stator circuit is kept constant and the input voltage v_a is varied in order to achieve a desired performance. The torque can be kept constant because the field current is kept virtually constant in the case of armature control. Since v_a directly determines the motor back emf drop due to resistance and inductance of the armature circuit, thus armature control is particularly suitable for speed manipulation over a wide range of speeds.

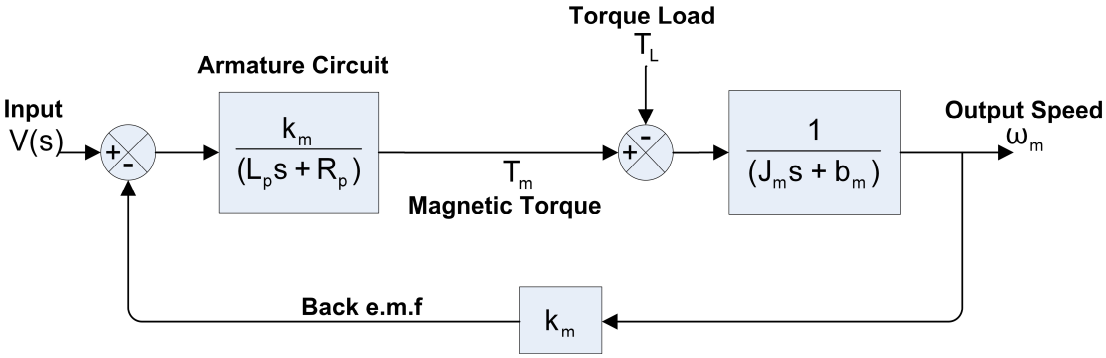


Figure 6.17 Open Loop Diagram for an Armature Control DC Motor

6.6.2 The Field Control

Here the armature voltage (and current) is kept constant and the input voltage v_f to the field circuit is varied. Since i_a is kept more or less constant, the torque will vary in proportion to the field current i_f. Since the armature voltage is kept constant, the back emf will remain virtually unchanged. Hence the speed will be inversely proportional to i_f. Therefore, by increasing the field voltage, the motor torque can be increased while the motor speed is decreased so that the output power will remain more or less constant in field control. Field control is particularly suitable for constant-power drives under varying torque-speed conditions, e.g. tape-transport mechanisms.

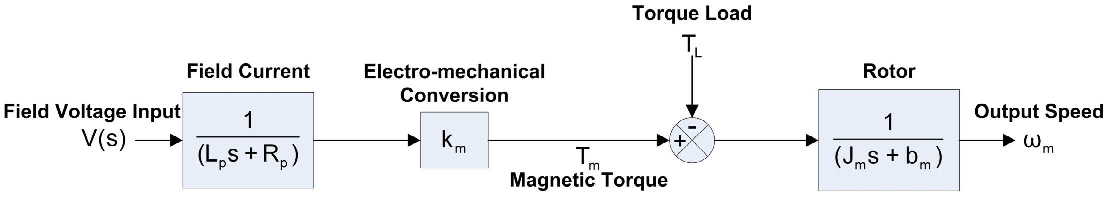


Figure 6.18 Open Loop Block Diagram for a field Controlled DC Motor

6.7 The DC Motor Control of the MSS Apparatus

For a DC servomotor to be controlled by a computer utilising mechatronic principles, the following hardware are required: a computer, an interface card, a drive controller circuitry and the DC servomotor itself. The interface card converts the digital signals generated by the computer into analogue signals which can be interpreted by the drive control circuitry. The interface card is therefore simply a D/A converter and depending on the type of card chosen, the card may have ports that can be used for data acquisitions as well.

The purpose of the driver control circuitry is to amplify or interpret the analogue/digital signals received from the interface card. The amplified signals are then used to drive the DC servomotors directly. Specifications on the motors' current and voltage requirements determine driver circuitry to be used and the specifications of the driver circuitry. A modular approach was implemented in designing the driver circuitry. This was done in order to reduce the cabling requirement and to ease the connection of the driver circuitry.

The MSS apparatus comprised of ten permanent magnet DC servomotors (refer to Chapter 3) in order to power the conveyor pallet transport system. For the pallet transport system, the oval conveyor configuration had to be flexible and interchangeable. The conveyor system comprised six sections, which included:

- Two straight sections, each driven by one 12V DC servomotor.
- Four 90^o curved sections, each section driven by two 12V DC servomotors.

The configuration of the conveyor parts and their driver motors is shown in Figure 6.19. For each pallet transport conveyer section the DC servomotors were required to drive inertial and frictional loads in both directions. The motor drive circuitry had to therefore incorporate a logic-decoding module that was capable of accepting transistor-transistor- logic (TTL) input signals containing direction information. The basic configuration of the modular design was to incorporate the power electronics for each section of the pallet conveyer system onto one drive module.

Each conveyor module was designed to drive tow DC servomotors, capable of direction switching. Based on the control information, the drive circuitry had to incorporate power electronics to enable an external power source to provide the high-power drive signals required to drive the DC servomotors (refer to Figure 6.20).

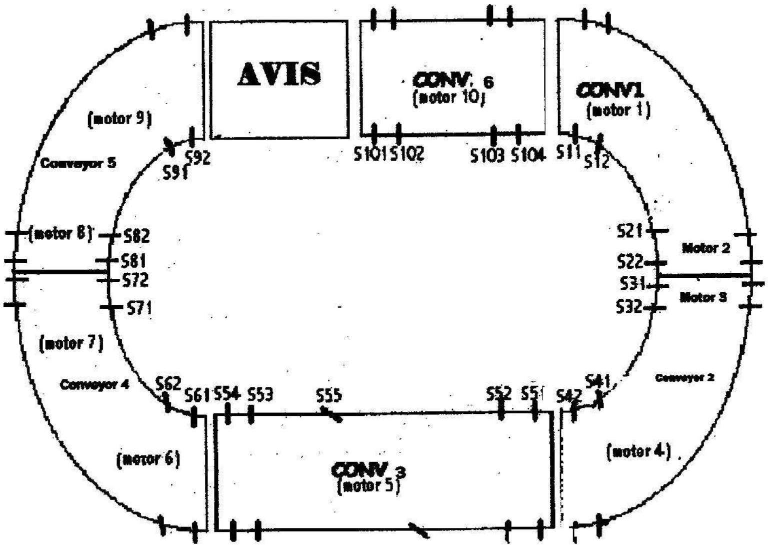


Figure 6.19 Configuration of Conveyor and drive motors

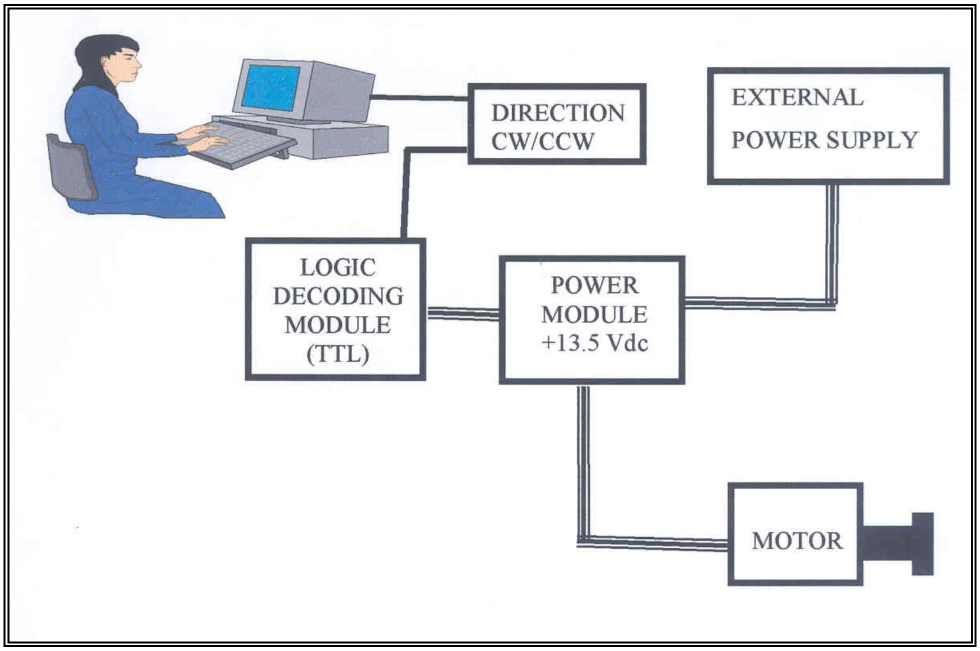


Figure 6.20 A schematic representation of the DC Motor Drive Circuitry

6.7.1 Pulse Width Modulation

The pulse width modulation (PWM) principle utilises chopper type circuits (Cetinkunt). The principle operates by applying the full supply voltage to the motor for short pulses of variable duration (ref Figure 6.21). This is done by timing the opening and closing of high frequency switch. In practice a power **MOSFET** (Metal-Oxide Field-Effect Transistor) is used to do this switching. A signal similar to the waveform desired across the motor is sent to the gate of the **MOSFET**, which is either open or closed with the signal to its gage being high (approx. 11V) or low (approx. 0V).

The value of the average voltage applied to the motor is varied by adjusting the ratio of the time that the 'switch' is closed to the period of switching. Advantages of the chopper circuit are that losses in a **MOSEFET**, just as in any semi-conductor, are less when operated in the saturated region as compared to operation in the linear region. This results in lower losses such as dissipation of energy as heat from the driver circuit.

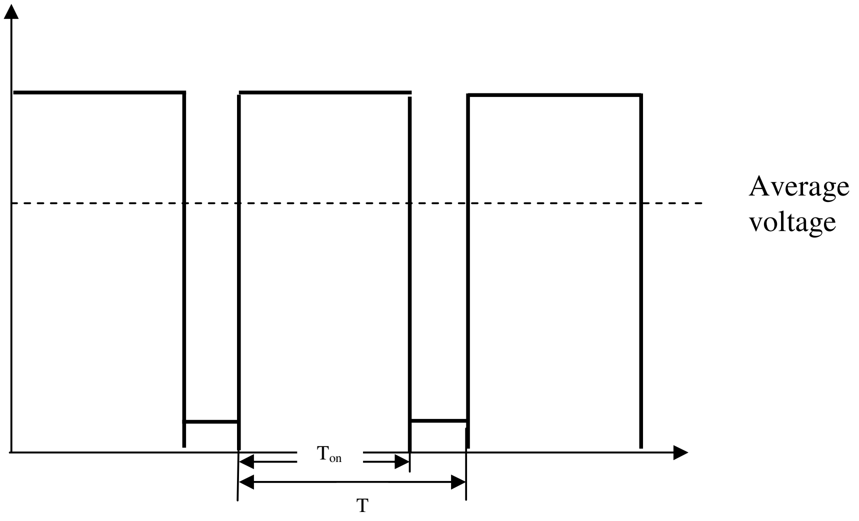


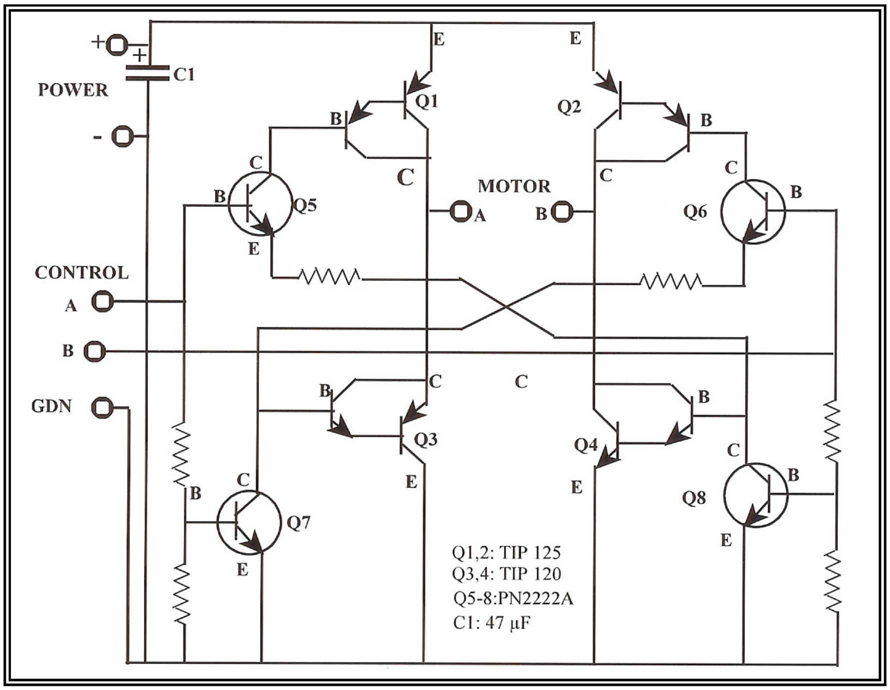
Figure 6.21 Output from a PWM circuit

The timing circuit which controls the switching of the transistors has small currents and negligible power passing through it and so does not suffer from heating effect such as drifting. Drifting occurs because parameters like current amplification are highly dependent on temperature and also differ from transistor to transistor. In practice, a frequencies motor operation will not be smooth and audible noise will be apparent.

6.7.2 The H-bridge Driver Circuit

The disadvantage of the PWM circuit is that it does not provide for direction reversal of the motor rotation. This would have to be done by a separate circuit using a double-pole double-throw (DPDT) relay configured specifically for polarity changing of the voltage fed to the motor, or by combining PWM with an H-bridge circuit. The H-bridge driver circuit (ref Figure 6.22) overcomes this by utilizing a push-pull approach. There are two logic level inputs to the H-bridge circuit, A and B. If input A is made high while input B is held low, output A goes high which then drives the motor in one direction.

If input B is made high while holding A low, output B goes high and drives the motor in the opposite direction. If both inputs are kept low, the motor is not driven and thus delivers no torque. To perform speed control, pulse width modulated signals must be provided to the inputs of the circuit. This results in the output to the motor following the waveform of the PWM input, resulting in the required speed control. Thus, the H-bridge driver circuit with PWM inputs obtains speed as well as direction control using only solid-state electronics. Since the circuit uses Darlington power transistors and current must flow through two transistors, forward losses are typically 1 and 2 volts. This is a significant volt drop when the maximum supply voltage is only 12V.



Q1,2: TIP 125
Q3,4: TIP 120
Q5-8:PN2222A
C1: 47 µF

Figure 6.22 H-Bridge Driver Circuit

6.7.3 The Amplifier Circuit [National Semi-conductor Co.,]

A dual package LM12 operational amplifier (see appendix C) wascan be used to configure a motor driver circuit. The LM12 is a high power audio amplifier component that consists of an internal H-bridge configuration and is capable of driving 35V at I0A while operating from 40V DC supplies. The monolithic IC can deliver 150W of sine wave power into a 40 load with 0,01% distortion. The power bandwidth is 60 kHz. Further a peak dissipation capability of 800W allows it to handle reactive loads such as transducers, actuators or small motors without derating. Important features of the LM12 include:

- Input protection;
- Controlled turn on;
- Thermal limiting
- Over voltage shutdown
- Output current limiting
- Dynamic safe-area protection

The IC delivers ± 10A output current at any output voltage yet is completely protected against overloads, including short circuit currents. The IC can withstand over voltages to 100V. The monolithic op-amp is compensated for unity-gain feedback, with a small-signal bandwidth of 700kHz. The LM12 can be paralleled or bridged for even greater output capability.

Figure 6.23 shows the LM12 driver circuit. The input reference signal to the LM12 is provided by the digital-to-analogue converters of the PC30G board. The circuit is biased for direction and speed control. The operating voltages of the circuit are 12V to 40V DC. To create a voltage rail that ranges from – 12V, two 12V batteries were used. These batteries were connected in series, so that the total volt drop across the two batteries was 24V. By using the common connection point between the two batteries as the 0V reference point, a +12V and a – 12V supply rails were obtained. The input reference signal to the LM12 driver circuit varies from -9V to +9V. The +9V causes the motor to rotate in one direction at full speed/power while -9V caused rotation in the opposite direction at full speed. At 0V reference input the motor is not driven. Intermediate values of reference input voltage causes corresponding proportions of motor output. The LM12 requires purely a voltage reference input as no current is drawn from the reference input.

The advantages of the LM12 driver circuit are:

- Low cost relative to other options
- Capable of handling high power
- Robust, able to withstand substantial over-voltage
- Compact
- Biased for speed and direction control
- Efficient, delivering 95% of supply voltage to motor (at full load)

The advantages and disadvantages of the circuits investigated were evaluated and the LM12 was found to present the most benefits to the application in the MSS apparatus.

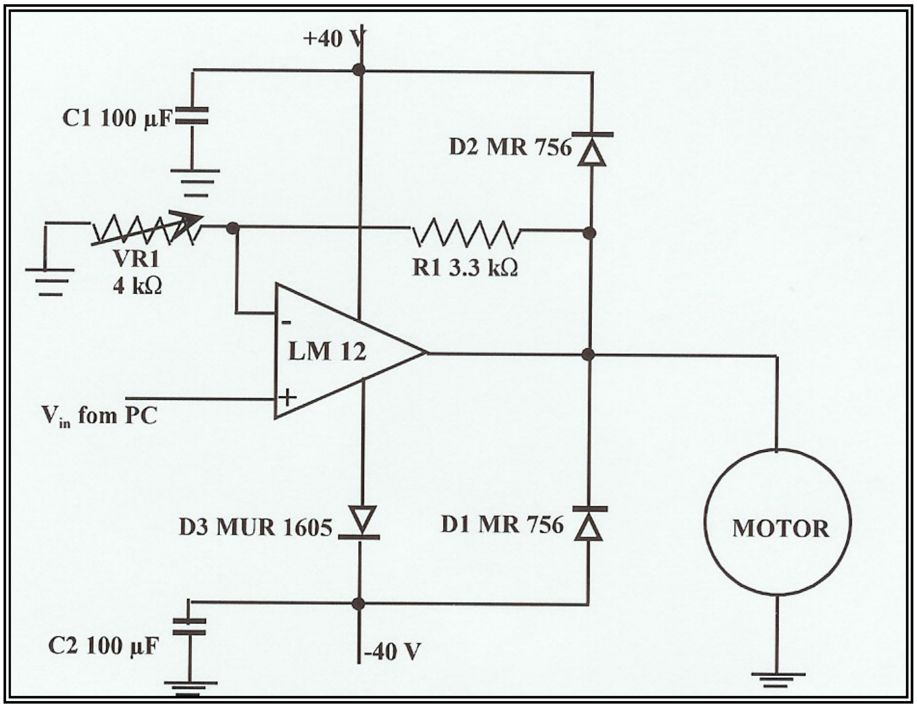


Figure 6.23 LM12 Driver Circuit

6.8 Chapter Summary

This chapter discussed the design of the power electronics drive modules used to control the stepper and DC servomotors in order to facilitate the operation of the MSS apparatus. This effected the pallet movement and manipulation within the conveyor system implementing synergistic design approach. The discussion also reviews the different motor types used in industry as well as electronic methodologies used to control and drive various motors.

Chapter 7

7 PC BASED CONTROL OF THE MSS APPARATUS

7.1 Introduction

This chapter presents the layout and positions of sensors implemented on the MSS apparatus to provide real-time feedback information and the methodology used to control the system. The electronic circuits of different sensors implemented in the system and their working principles are also presented. A brief review of signals and signal conditioning which was critical for accurate and efficient data acquisition and analysis is also given. The chapter concludes by describing the development of the software coded algorithms implemented in control the MSS apparatus. There is also a discussion of the input-output (I/O) interface board that used and a thorough description of the coded algorithms for different systems of the MSS apparatus.

The MSS apparatus employed in the research used low-cost sensors to provide real-time information about the different pallet positions and the actuation of modular conveyor system. The control of the MSS apparatus was thus a close loop system at points where sensors were positioned. Mechatronic sensory feedback was achieved by implementing the correct sensors with the relevant sensory circuitry.

7.2 Layout of Position Sensors

The modular conveyor system transported the work piece on a pallet from the individual CIM cell components (ref. Chapter 4). The control of the conveyor system required the implementation of a feedback system that was capable of accurately monitoring the position of the work piece and pallet along the conveyor track. The work piece on the pallet had to be tracked and delivered to the correct part processing stations. The conveyor system consisted of roller conveyors that formed part of the modular computer integrated manufacturing system into which the PC-based robot was integrated.

The control resolution required the pallet to be accurately positioned and transported. An innovative byte array feedback technique was developed to obtain feedback information from the part conveyor system. A total of twelve (12) pairs of emitter-receiver type of sensors were mounted at strategic positions along the conveyor and implemented to monitor the pallet position and were interfaced directly to two 8-bit port of a computer interface card.

The conveyor system was further sub-divided into 6 sections comprising of 4 quadrant sections and two straight sections (see Figure 6.19). The value of the byte read from the interface ports was cross-referenced against a list of possible values in order to determine the position of the pallet along the conveyor as well as actuating the system. The critical sensor points were positioned to monitor the pallet leaving and entering the conveyor zone.

As there are six modular conveyor sections, one sensor pair was placed at each conveyor end. Extra pairs of light dependant resistor (LDR) sensors were placed at the AGV docking station and PC-based robot material handling station. The critical sensing points were implemented using long-range infrared (IR) switches. Each of the IR switch modules comprised of a transmitter and a receiver unit. As the leading edge of a pallet would arrive at a sensor point, the beam would be broken. Once the trailing edge of some pallet passes the sensor point, the receiver is once again irradiated and the beam is restored (see Figure 7.1). The wiring diagram of the sensor pairs and motors positioned along the conveyor are in Figure 7.2 and Figure 7.3 respectively.

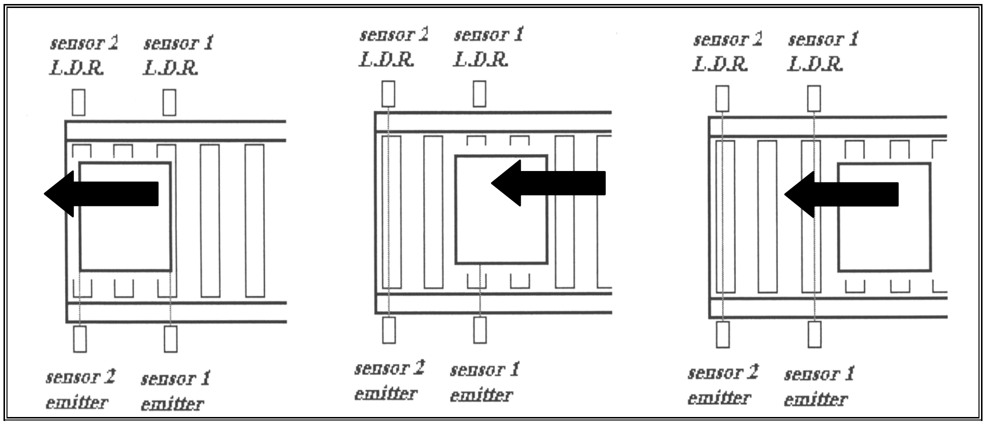


Figure 7.1 IR pairs Configuration in the Conveyor System

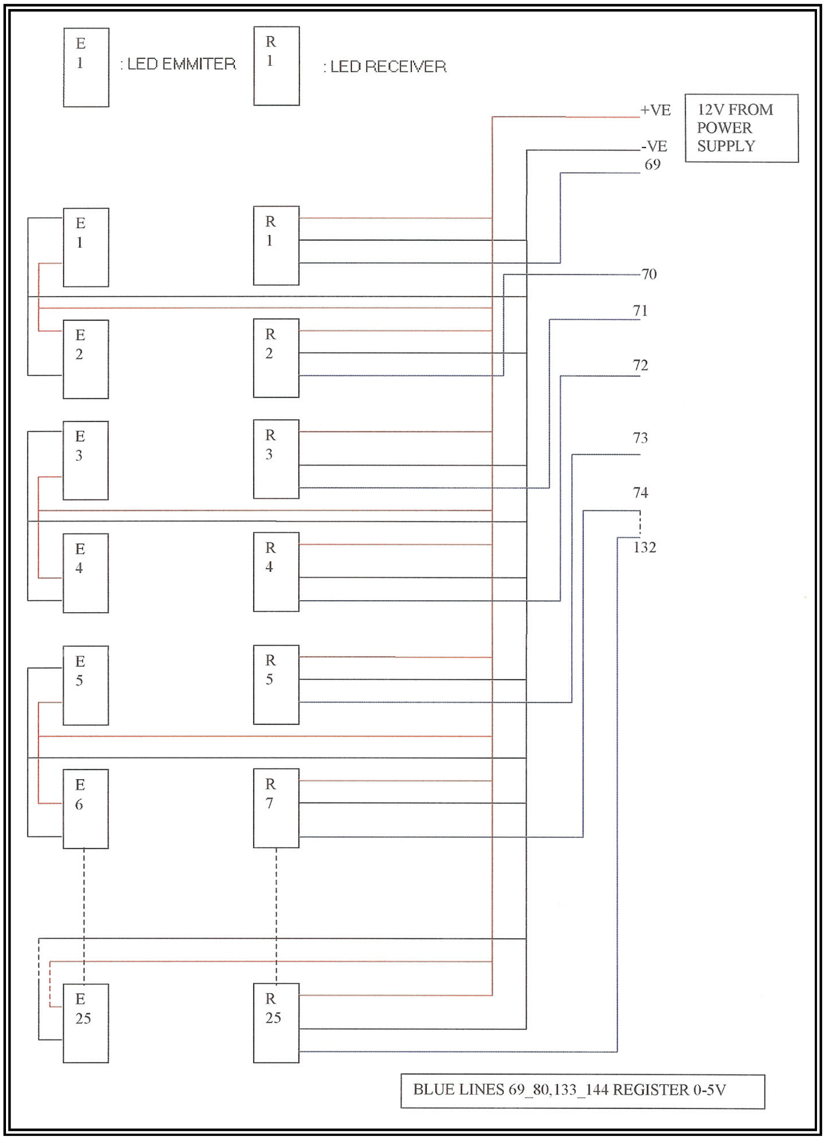


Figure 7.2 Wiring Diagrams of the Conveyor Sensors

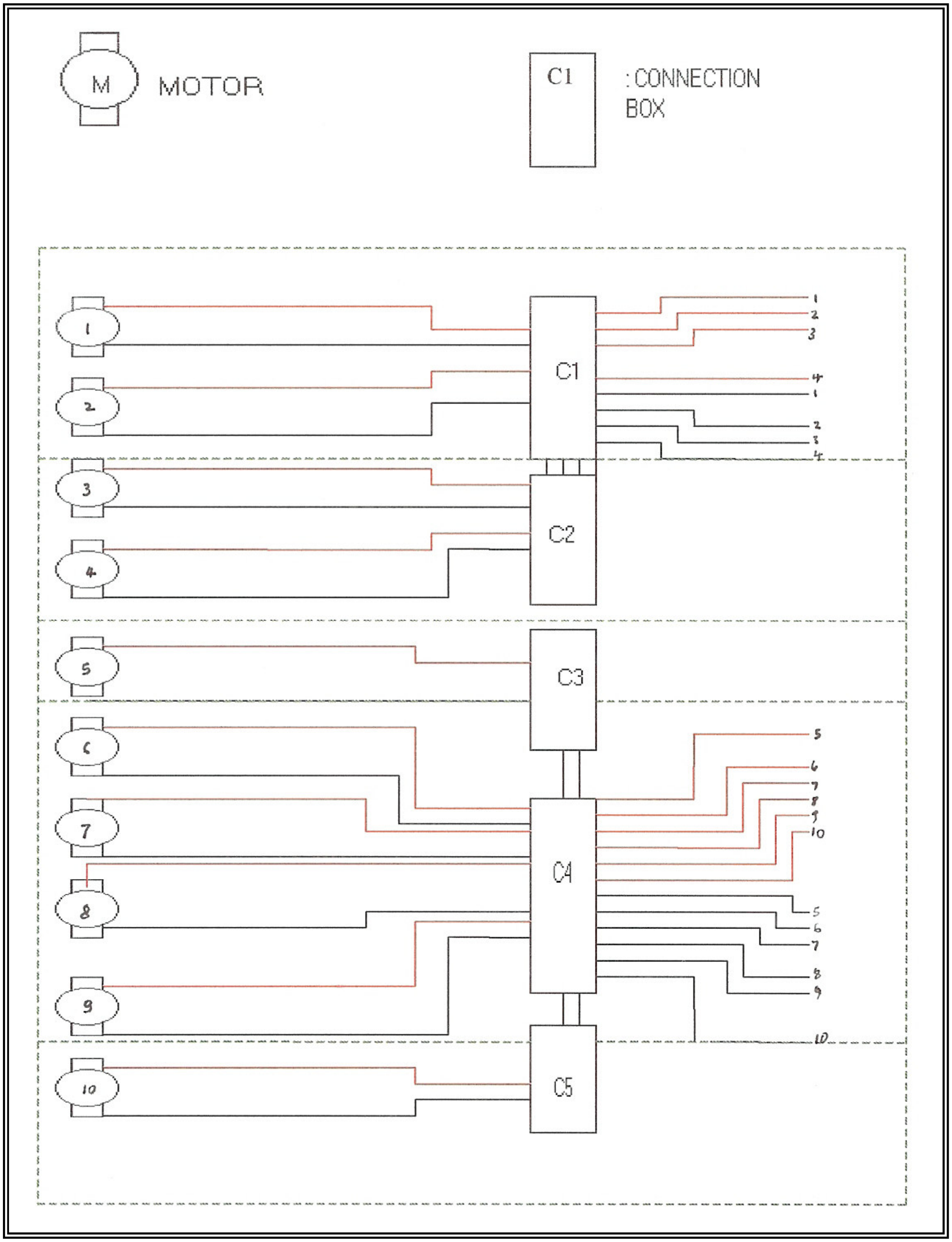


Figure 7.3 Wiring Diagram of the Conveyor Driver Motors

7.3 Long Range IR Transmitter Circuit

Figure 7.4 shows the long-range infrared transmitter circuit. The circuit uses a 4016-oscillator circuit to generate waveform with a short duty cycle with a greater percentage of the period being spent in the low state as opposed to the high state. The frequency pulse train set by resistors R1 and R2 must be significantly higher than the scanning frequency at which the states of the individual sensors are monitored. The modulated signal is used to bias the base-emitter circuit of the field effect transistor, TR1. The infrared emitter, IRD1, is connected in the collect-emitter (drain-source) circuit of TR1 capacitor C2 and connected across it. The capacitor is charged by the supply when the transistor is not biased. When the current flows in the collector-emitter circuit, the capacitor discharges through the diode resulting in a high current spike that dramatically increases the power of the diode. Furthermore the short duration of the pulses ensures that the transmitting diode will not burn out. The capacitor group, C3 and C4, decouple the supply from the circuit in order to smooth out the high amplitude switching transients of the supply voltage, thereby eliminating the noise and upholding the integrity of the transmitted pulse.

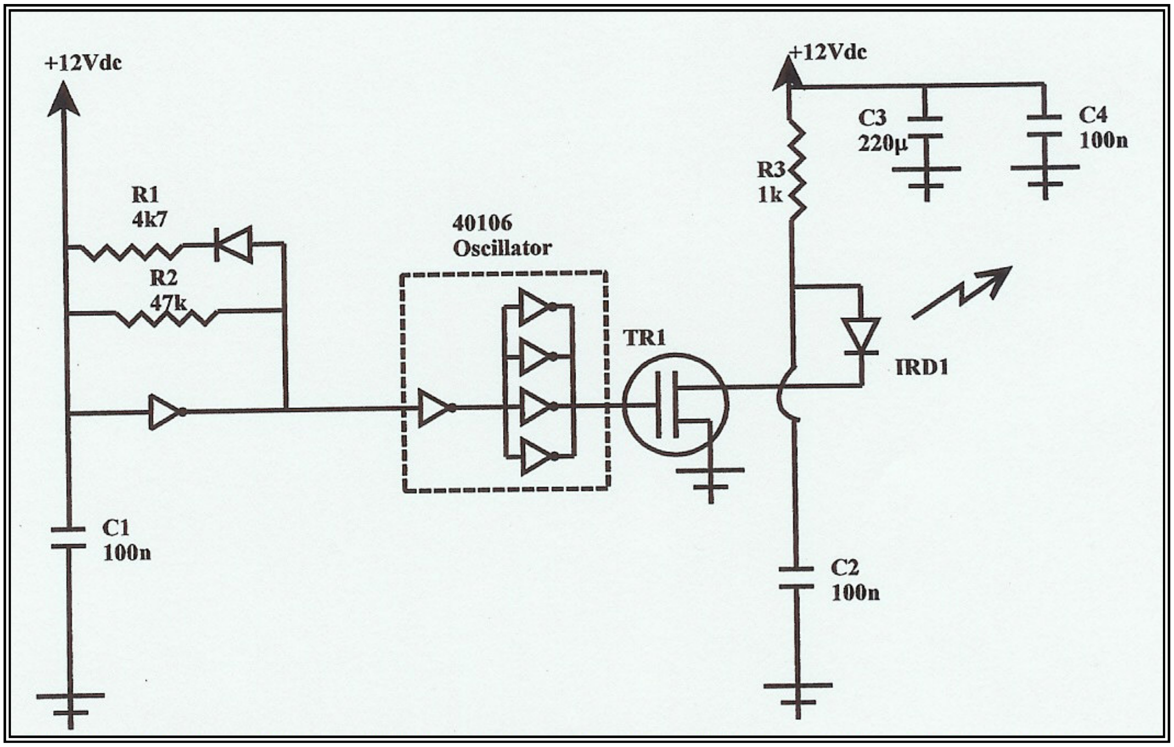


Figure 7.4 Long Range Infrared Transmitter Circuit

The receiver circuit is based on a 12V DC phototransistor, TRI (ref Figure 7.5). The phototransistor is biased by the intensity of infrared radiation detected at its base-emitter junction. The photo-transistor receives a high frequency radiation pulse which results in the switching of the collector-emitter current thereby necessitating the use of AC coupling capacitors, C3, C4 and C5 (ref Figure 7.5). Since the current in the collector-emitter circuit is dependent on the intensity of the detected radiation, the output from TRI is coupled via capacitor C3 to the base of transistor TR3 that forms the second half of the Darlington pair.

The output from transistor TR3 is coupled to a modulating circuit, R4 and R5 that allows a small additional current to flow from the supply through R5. Therefore the pulse train generated by TR1 and TR2 is modulated and as a result does not display the current fluctuations of the phototransistor collector-emitter circuit. The stabilised pulse signal is applied to the base of the transistor TR4. The TR4 collector-emitter circuit performs a simple level shifting function that reduces the supply voltage to TTL level using-potential divider resistance pair, R6 and R7. The output O/P is pulled high when TR4 is not biased; resistor R6 is not irradiating i.e. the phototransistor. The polarized capacitor C6 decouples the output signal thereby reducing the ground noise interference in the output signal. The photographic diagram for the emitter-receiver light sensor circuit is shown in Figure 7.6.

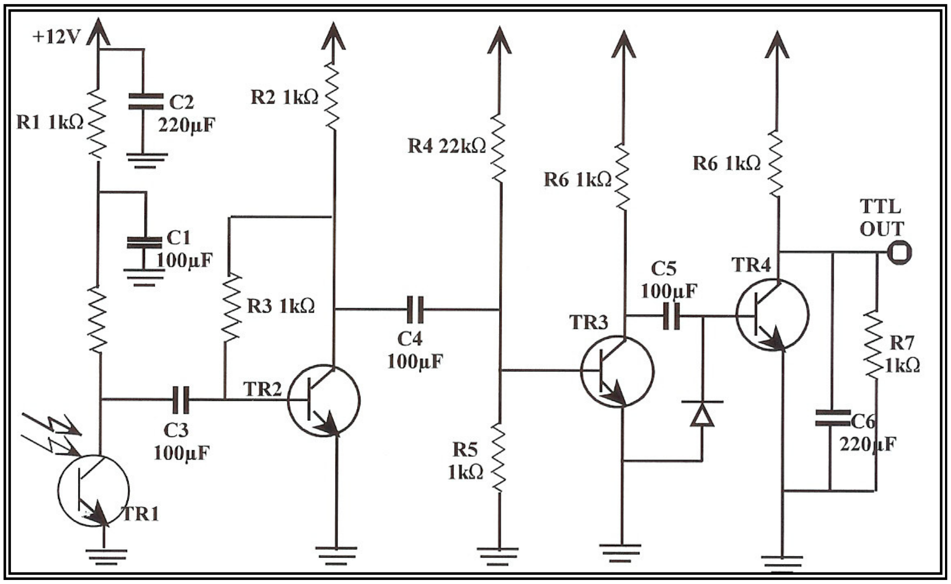


Figure 7.5 The Infra-Red Receiver Circuit

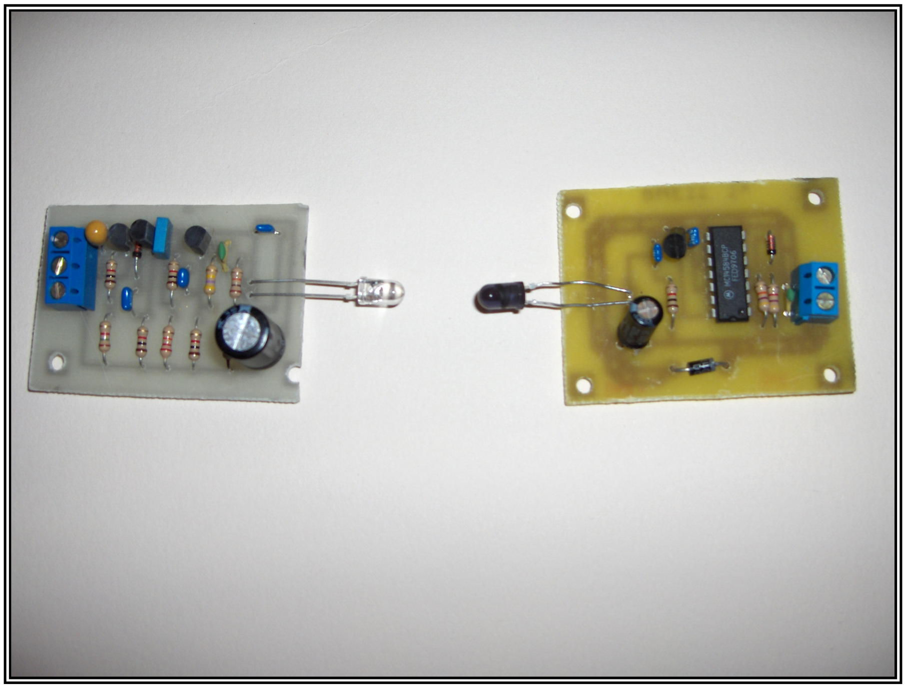


Figure 7.6 Emitter and Receiver Light Sensor Circuits

7.4 Light Dependent Resistor (LDR) Circuitry

One type of light dependent resistor (LDR) circuit was used in the MSS apparatus. Each LDR was fitted inside a black plastic tube to minimise the amount of stray light reflected onto the sensor. LDR circuits were used to determine the position of the pallet on the conveyor during docking of AGV. The leads of the photo-resistors, after being insulated, were fitted inside black plastic tubes of 7 mm and 4 mm external and internal diameters respectively. This set up provided the LDRs with shielding from ambient light. The depth of the LDR head inside the second tube determined the light's threshold value for activating the photo-resistors circuitry. The further away the head from the top of the second tube, the higher the light's threshold value. The resistance of the light detector (LDR) varies with the intensity of incident light on it. Its resistance decreases with increasing intensity of incident light. Objects passing above the LDR fitted into a tube decreased the amount if incident light on the LDR which resulted in the increase of the LDR's resistance.

A 12V DC LDR implemented in this project formed a part of a transistor digital circuit (ref Figure 7.7). The circuit uses the resistance value of the LDR to output five volts when an object moves across the hole of the tube enclosing the LDR. This is equivalent to a TTL (Transistor-Transistor Logic) high value. When the object moving across the tube and the light is not being blocked, an output of zero volts (TTL low value) is sent by the transistor digital circuit. The TTL output values of the circuit were required so that the signals could be sent to the interfacing card for processing. The 5V DC diode is used in series to a 3.6 MΩ to channel the current to the transistor circuit. When the resistance of the LDR is high, current flows through the 4.7 kΩ and to the transistor collector and the output V_{out} will then be 5V. When the resistance of the LDR decreases, current flows through it to the emitter and this results in the output V_{out} being 0 V.

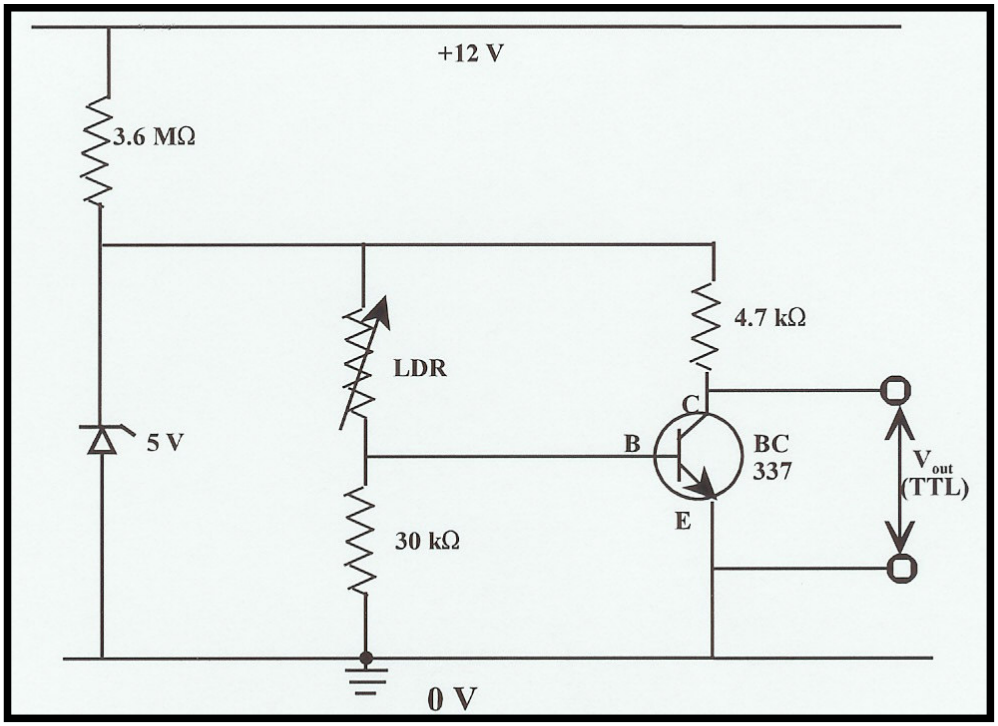


Figure 7.7 LDR Transistor Digital Circuit

7.5 Signals

A 'signal' is a time-varying phenomena for voltages and currents used to convey a message or information from one place to another. The output measured from a sensor is a signal and it contains some useful information. Before the signal can be interpreted the type of signal as well as the desired end result must be known. These parameters determine the type of analysis techniques, interface equipment and any related hardware that must be used. Signals can be classified as either digital or analogue. A digital (or binary) signal had only two possible and discrete levels: a high level and a low level. Digital signals can be further classified as on-off signals or pulse-train digital signals (ref Figure 7.8). A digital state detector is required to determine whether the signal is a high level or a low level signal. The on-off high and low level signals are generally referred to as transistor-transistor logic (TTL) switching signals. On the other hand the pulse-train is a series of state transitions. To measure a pulse train signal, an instrument must be able to detect and count digital transitions. Incremental encoders are examples of pulse-train transmitting devices.

Analogue signals contain varying information over some time domain and amplitude range. Thus, the magnitude of these signals can have an infinite number of values that are within the amplitude range. Analogue signals can also be further classified as being either DC or AC signals. Analogue DC signals are static or slow varying signals, with the important characteristic that the signals are conveyed in the level or amplitude of the signal in a given instant. The measurement of the DC signal involves an instrument that can detect the level of the signals. The most common component of analogue signal is thus converted to a digital signal that the computer can interpret. Analogue time domain signals are distinguished by the fact that they convey useful information with varying time. Analogue AC signals generate waveforms where the shape of the waveform is of most interest.

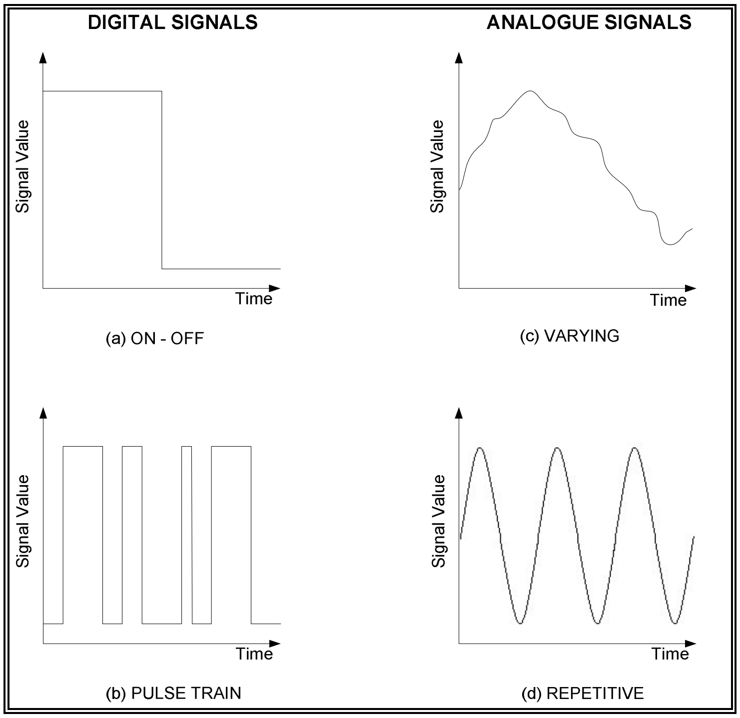


Figure 7.8 Signals

7.6 Signal Conditioning

PC based data acquisition (DAQ) systems and plug-in boards are used in a wide range of applications. Typically, general purpose DAQ plug-in boards are used for input and output analogue and digital measuring voltage signals. Many real world transducers' output signals must be conditioned in some way before a DAQ board or measuring system can accurately acquire the desired signal. Signal conditioning is the front end pre-processing required converting the electrical signals received from transducers to signals which DAQ plug-in boards or other forms of data acquisition hardware can accept. In addition, many transducers require excitation currents or voltages, Wheatstone bridge completion and linearization to allow accurate measurement of the required signal. Therefore, most PC based DAQ systems include some form of signal conditioning equipment.

The fundamental functions which signal conditioning equipment performs are:

- Amplification
- Isolation
- Filtering
- Excitation
- Linearization

The type of signal conditioning equipment required and how it is interfaced within the DAQ system is largely dependent on the number and type of transducers, their excitation and earthling requirements and no less importantly, how far the transducers are located from the PC which must acquire analyses and store the transducer signal data.

7.6.1 Amplification

Amplification is one of the primary tasks carried out by signal conditioning equipment. It performs two important functions,:

- Increases the resolution of the signal measurement.
- Increases the signal-to noise ratio (SNR)

Amplification is primarily used to increase the resolution of the signal measure. Consider a low level signal of the order of a fraction of a mV, fed directly to a 12-bit A/D converter with a full scale voltage of 10 V. The highest possible resolution can be achieved by amplifying the input signal so that the maximum input voltage swing equals the maximum input range of the ADC. Another important function of amplification is to increase the SNR. Where transducers are located a long way from the data acquisition board and the signal measurements are transmitted through an electrically noisy environment, then low level voltage signals can greatly affected by noise. Where the low-level signals are amplified at the date acquisition board after they have been transmitted through the noisy environment, then any noise superimposed on the signal will also be amplified by the same amount as the signal. If the noise is of the same order of magnitude as the signal itself (i.e. SNR is low), then the signal measurement may be lost in noise, leading to inaccurate and meaningless measurements.

7.6.2 Isolation

Isolated signal conditioners pass a signal from its source to the measurement device without a galvanic or physical connection. The most common methods of circuit isolation include opto-isolation, magnetic or capacitive isolators. Opto-isolation is primarily used for digital signals. Magnetic and capacitive isolators are used for analogue signals, modulating the signal to convert it form a voltage to a frequency and transmitting the frequency signal across a transformer or capacitors without a direct physical connection before being converted back to a voltage. Isolation performs several important functions. Firstly, isolation provides an important safety function by protecting expensive computer equipment and DAQ board, as well as the equipment operators, from high voltage transients which could be caused by electrostatic discharge, lightning, or high voltage equipment failure.

While isolated signal conditioning equipment provides an effective physical barrier and transient voltage protection for the computer and DAQ equipment, typically up to 1500V, separate over voltage protection is usually provided at the input(s) of the signal conditioning equipment to prevent internal damage to the signal conditioning equipment itself. In medical applications, isolation prevents the possibility of potentially fatal voltage or current signals from reaching sensors or transducers attached to or implanted in the human body.

Another important function of isolation is to ensure that the accuracy of measured signals is not affected by ground loops or common mode voltages. Ground loops, caused by a potential difference between the source ground and the ground reference of the measuring device, may cause inaccuracies in the measured signal, or if too large may damage DAQ equipment. Using isolated signal conditioning modules will eliminate the ground loop, and ensure that the signals are accurately measured.

7.6.3 Filtering

Filtering removes unwanted noise from signal measurements before they are amplified and presented to the A/D converter. In intelligent signal conditioning modules, integrating A//D converters go a long way to averaging (filtering) out any cyclical noise appearing at the input. Alternatively, software averaging may also be used to digitally filter out periodic noise signals such as mains hum. This technique involves taking many more measurements that is necessary to acquire the wanted signal, then averaging them to produce a single measurement. If the samples are averaged over the period of the cyclical noise signal, then this signal will be averaged to zero. Where there is no other form of filtering, an analogue hardware filter provides the cheapest option. There are two types of analogue filter namely passive filters which use only passive components such as capacitors and resistors, and active filters which also utilize operational amplifiers. Ideally, filters should eliminate all data at frequencies outside the specified frequency range, providing a very sharp transition between the frequencies that are passed and those that are filtered out. Most practical filters are not ideal and do not usually eliminate all the undesirable amplitude components outside a specified frequency range.

Attributes common to filters are:

- **Cut off Frequency**

This is the transition frequency at which the filter takes effect. It may be the high pass cut-off or the low-pass-cut-off frequency and is usually defined as the frequency at which the normalized gain drops 3db below unity.

- **Roll-off**

This is the transition frequency at which the filter takes effect. It may be the high pass cut-off or the low-pass cut-off frequency and is usually defined as the frequency at which the normalized gain drops 3 db below unity.

- **Quality factor**

This variable is an adjustable characteristic of a tuned filter and determines the gain of the filter at its resonant frequency as well as the roll-off the transfer characteristic either side of the resonant frequency. Active filters are more frequently used since they provide a sharper roll-off and better stability. These filters are low pass filter, high pass filter, band pass filter, band notch filter, and butter worth filter.

7.6.3.1 Low Pass Filter

Low Pass Filters pass low frequency components of the signal and filter out high frequency components above a specific high frequency. An active low pass filter is shown if Figure 7.9

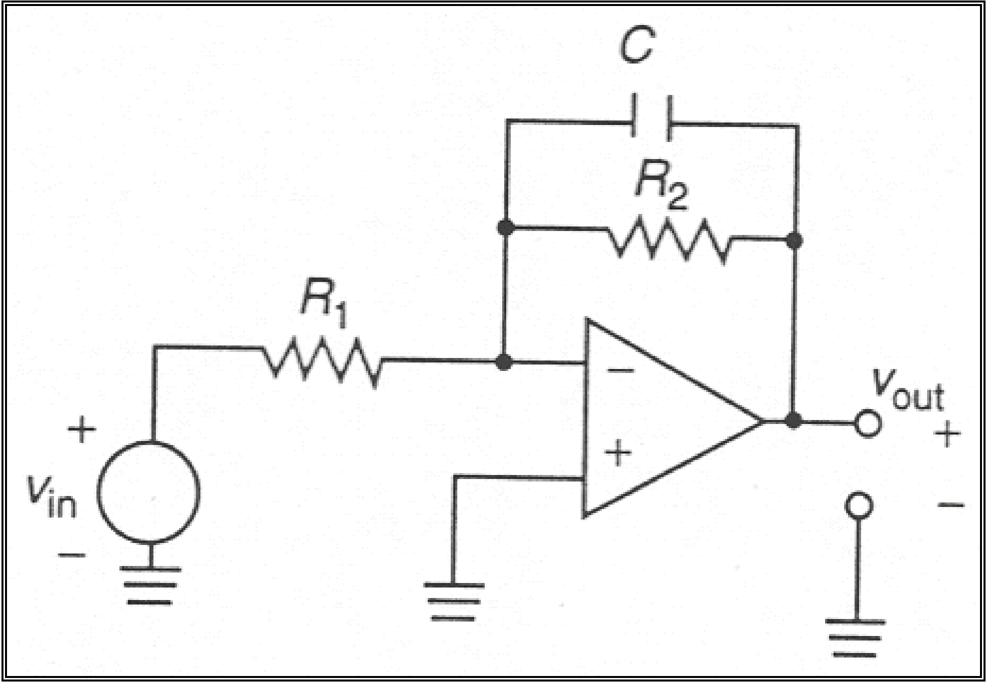


Figure 7.9 Active Low Pass Filter

The gain of this filter is given by:

$$A_{LP(jw)} = H_0 \frac{1}{\sqrt{2}};$$
$$A_{LP(jw)dB} = 20\log_{10} H_0 - 20\log_{10} \sqrt{2} \qquad \textbf{7.1}$$
$$A_{LP(jw)dB} = 20\log_{10} H_0 - 3dB$$

This means that the filter rolls off at 20dB per 10 times in increase in frequency (20dB/decade) times the order of the filter as shown in Figure 7.10.

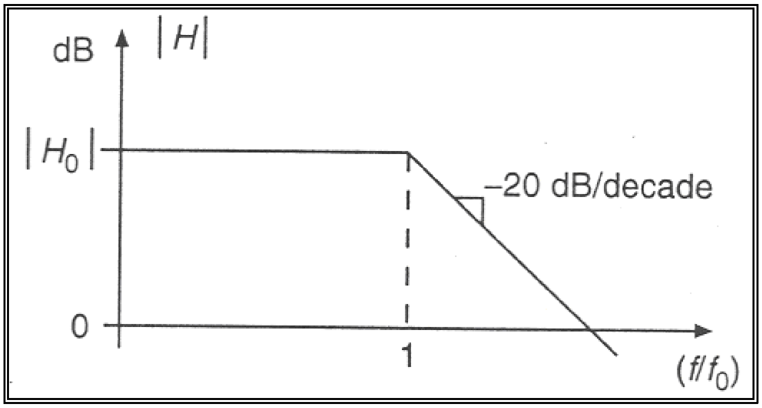


Figure 7.10 Frequency Response of a single pole Low Pass Filter

7.6.3.2 High Pass Filter

High Pass Filter passes high frequencies and filter out low frequencies beginning at a specific low frequency. An active high pass filter is shown in Figure 7.11 and the transfer characteristics of an ideal high pass filter is shown in Figure 7.12.

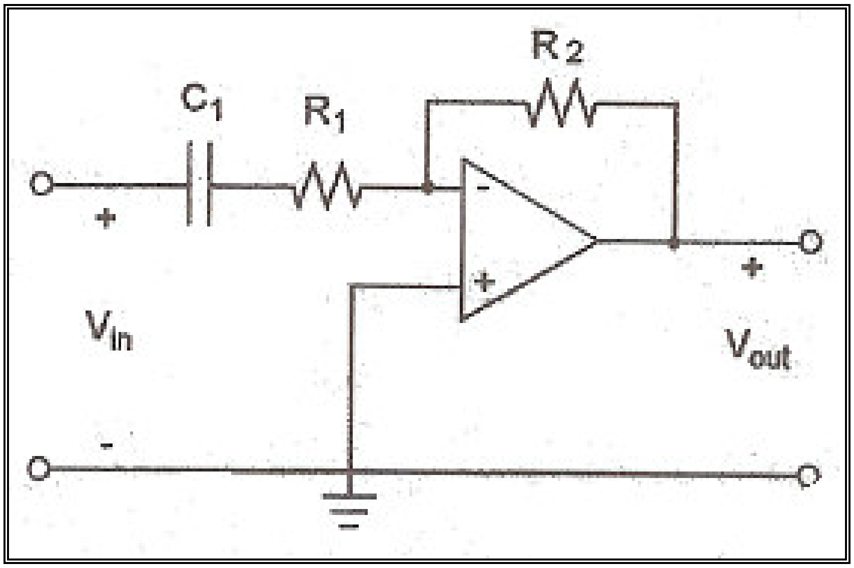


Figure 7.11 Active High Pass Filter

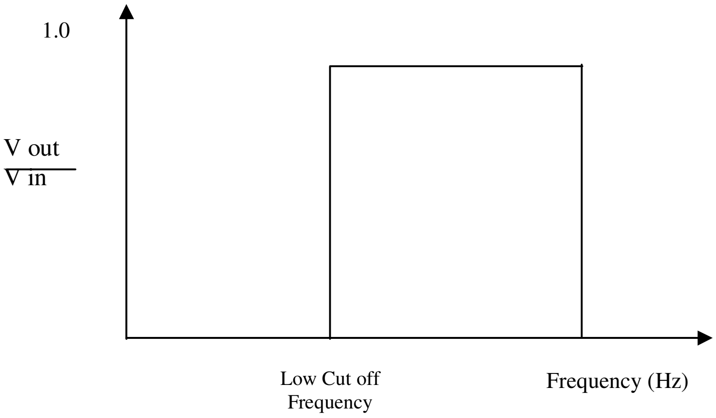


Figure 7.12 High Pass Filter Transfer Characteristics

7.6.3.3 Band Pass Filters

Band Pass filters only those frequencies within a certain range specified by a low and high cut-off frequency. There are also the band Stop (Notch) Filters that filters out a certain range of frequencies specified by a start and stop frequency, and passing all others. These filters combine a high pass and a low pass in parallel, each tuned to the low and high cut-off frequencies respectively.

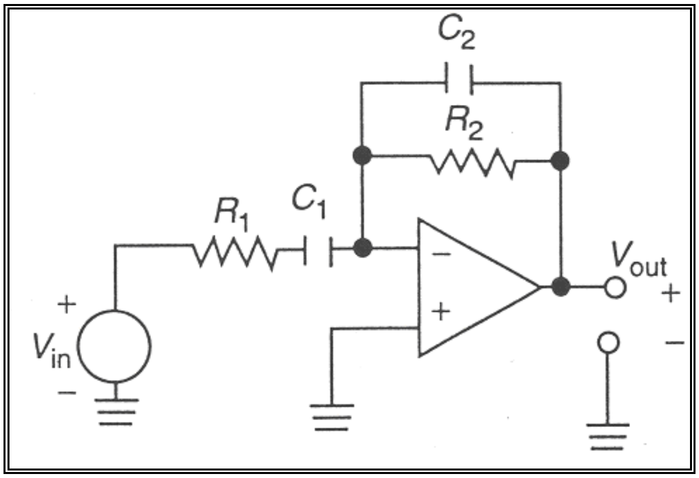


Figure 7.13 Band Pass Active Filter

7.6.3.4 Butterworth Filter

Butterworth filters provide a higher level of low pass filtering, containing two or more low pass filter stages. The number of stages 'n' of the filter determines how sharp the roll off is at the cut-off frequency. A two stage filter of this type is known as a second order Butter worth filter as shown in Figure 7.14.

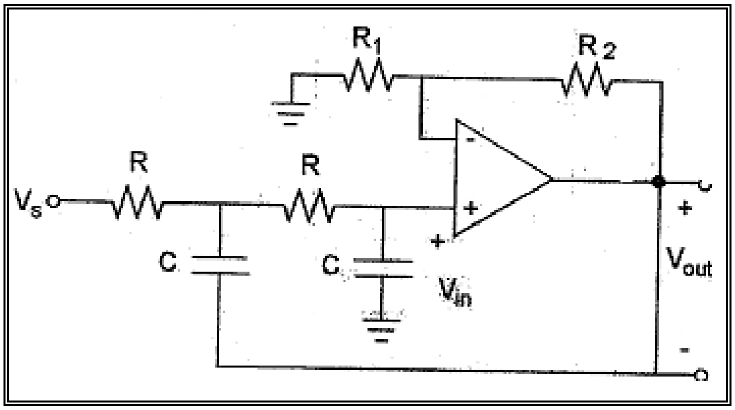


Figure 7.14 Two Stage Butterworth Filter

7.7 Linearization

The output signals from transducers such as thermocouples exhibit a non-linear relationship to the phenomena being measured over a given input range. Linearization of these signals is typically performed by the data acquisition software. However, where the non-linear relationship is predictable and repeatable this task can be performed by intelligent signal conditioning hardware. This typically requires the signal conditioning equipment to be programmed for a particular type of transducer, but once completed, the measurements returned to the host PC or stored as part of the measurement process are directly related to the phenomena (e.g. temperature) being measured.

7.8 PC Based Control of the MSS Apparatus

Mechatronics represents an approach to the design of engineering systems which involves the integration of mechanical engineering, electrical and electronic engineering with software engineering and computer technology at all levels of the design process [Craig]. This section discusses the mechatronic principles used to collect positional feedback information used in the control of the independent motion systems of the MSS apparatus. The implementation of low cost industrial electronics to collect real-time feedback information pertaining to the status of the MSS apparatus is discussed highlighting the sensors connected in parallel to the digital I/O port. The operator based mechatronic control principle of the MSS apparatus is depicted diagrammatically in Figure 7.15.

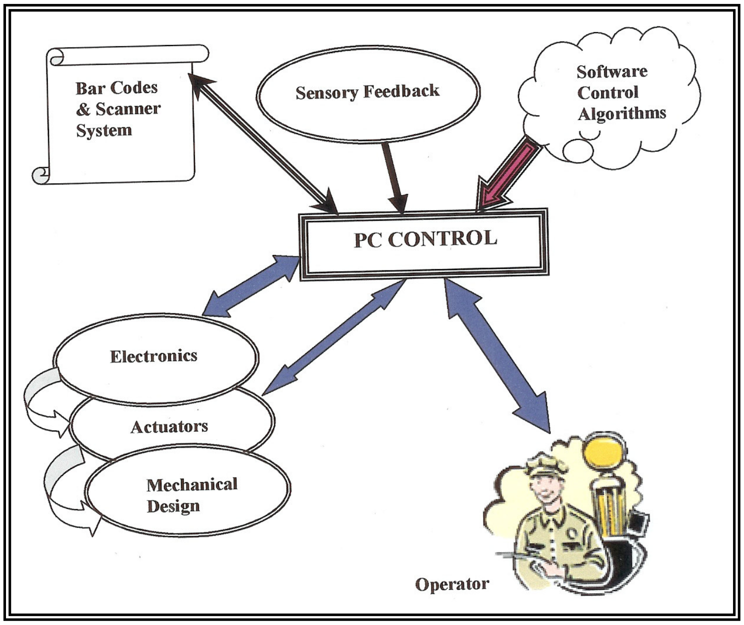


Figure 7.15 PC Based Control Principle of the MSS Apparatus

7.8.1 Digital Interfacing

The two states were defined by the voltage ranges, a high range where c<V<d (Ref. Figure 7.16). The MSS apparatus implemented a digital I/O control system that was based on the transistor-transistor-level (TTL) system for the digital signal voltage ranges. The digital signal conveyed the information in either of the two states namely: HIGH/LOW, TRUE/FALSE and ON/OFF etc.

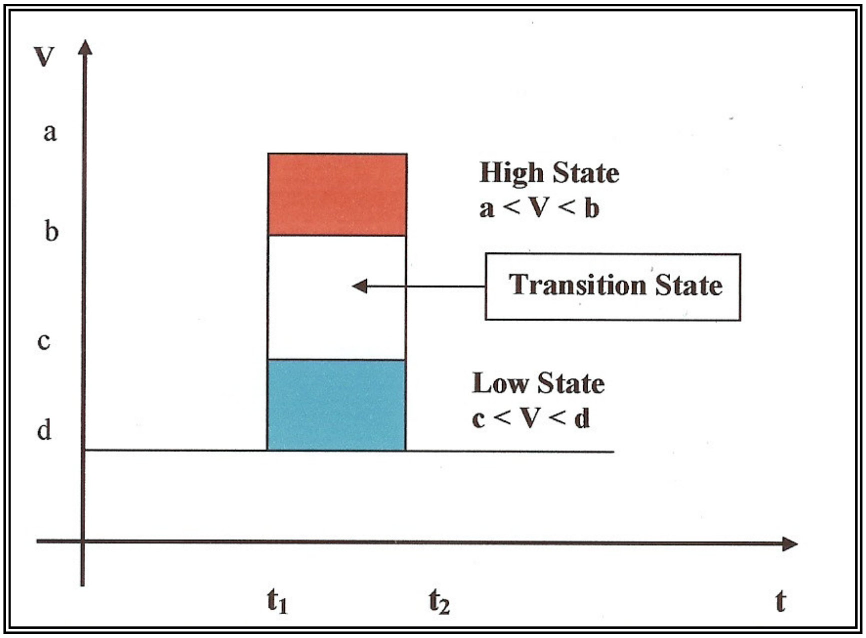


Figure 7.16 Digital Signal Information Conveying System

7.8.2 The Eagle PC30GA I/O Interface Card

An I/O analogue and digital interface board was implemented to acquire data from sensory circuitry of the MSS apparatus and to send the control signals to different drive circuits of the MSS apparatus. Seventeen (17) sensors with circuits and seventeen (17) TTL outputs were implemented. Three driver circuits requiring twelve (12) TTL input signals and three (3) driver circuits requiring three (3) analogue input signals were implemented. The requirement on the interface board was that it had to have at least seventeen (digital) input lines, twelve (12) digital output lines and three (3) analogue output lines. The PC30GA board was chosen as the data acquisition card to be to be implemented in the control system for the MSS apparatus as it provided sufficient analogue and digital I/O. Microsoft Visual Basic 6 (VB6) was used to communicate with the PC30GA card which is controlled via library of high level functions stored in the dynamic link library, *edr32,dll*.

The PC30GA series board developed by Eagle Technology (ref. Figure 7.17) is a low cost, high accuracy analogue and digital I/O board. The PC 30 series allows the board features to be controlled by software. The PC30GA board has a throughput of kHz with four digital to analogue converters (DACS) which produces analogue output voltages of –10 to +DC. The DACS were used to send analogue signals to the driver circuits.

The board features sixteen (16) single ended or eight (8) differential analogue to-digital inputs with software programmable gains of 1, 10, 100 and 1000. In single ended input connections, input signals share a common low side, which is analogue ground. Different inputs use two multiplexer switches per channel. The A/D converter measures the difference the high and the low input lines of each channel. Differential input configuration is the best suited for eliminating system noise.

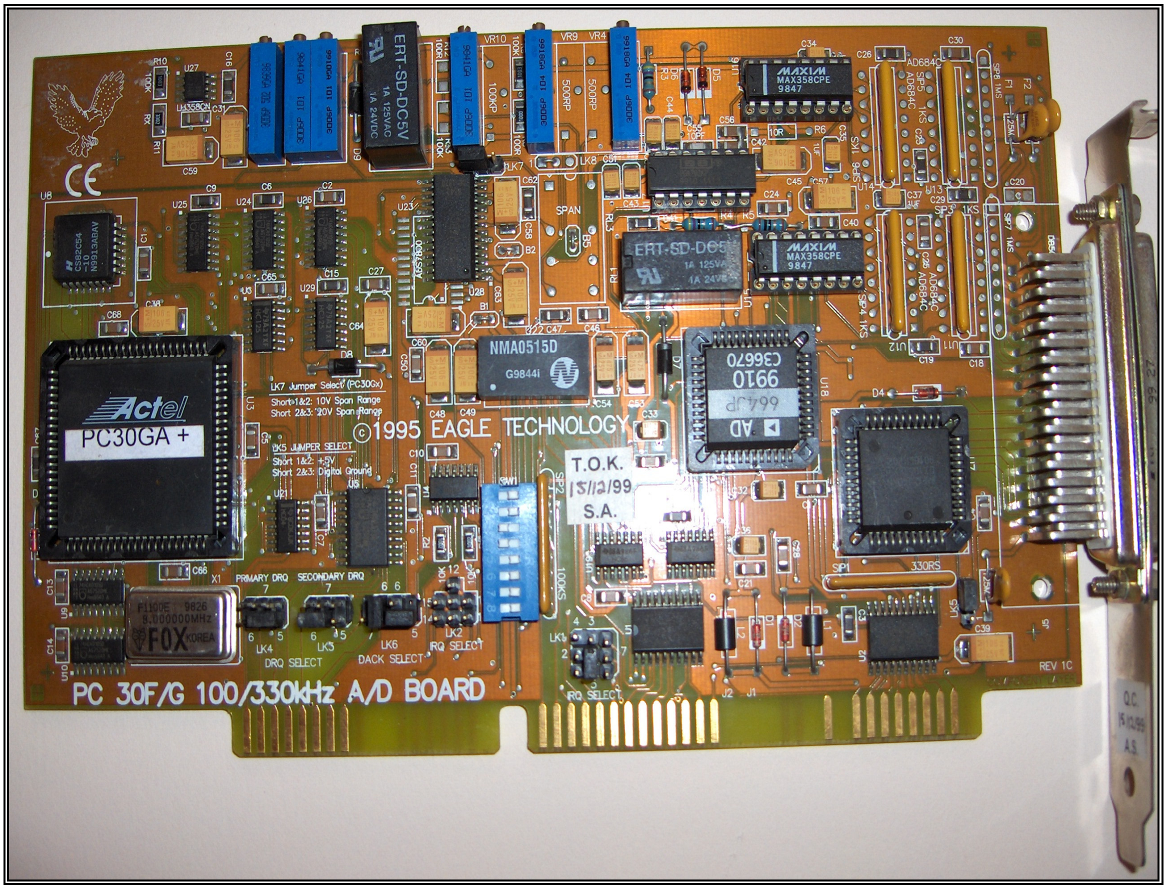


Figure 7.17 The Eagle PC30GA I/O Interface Card

The board also features three (3) digital I/O ports with 8 lines per port, allowing twenty-four (24) digital I/O lines. The ports can be configured into two digital output ports (sixteen input lines) and one digital input port (eight lines), or one digital output port and two digital inputs ports. The former configuration of the ports implemented. The PC30GA board has an onboard sixteen bit counter that allows real time timing applications such as PID control (Appendix D). The card is provided with instrument drivers for graphical programming languages such as Lab View and Visual Basic.

When the PC30GA interface card was connected directly to the external circuitry, too much current could be drawn from it or too much current can be supplied to the board. In order to protect the interface board from the overload currents of the external circuitry, a simple voltage follower circuit using an operational amplifier was implemented (see Figure 7.18). The signal from the PC30GA card, or the signal from the external circuitry, was applied at the non-inventing pin of the operational amplifier. Thus the amplifier circuit drew no current from the input circuit, because the amplifier had infinite input impedance. Thus,

$$\mathbf{I_+ = I_-} \qquad \textbf{(7.2)}$$

The inverting pin and the lead of the external circuitry/ PC30GA card were connected to the output pin of the operational amplifier. Since the amplifier had an infinite gain, the difference between the input voltage should be zero, otherwise the output would be infinite. Thus;

$$\mathbf{V_{in} = V_{out}} \qquad \textbf{(7.3)}$$

And finally, the operational amplifier had zero output impedance. Therefore, output voltage did not depend on the output current.

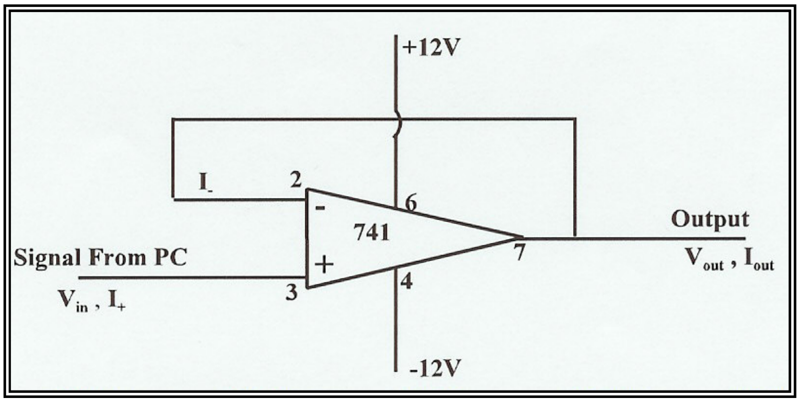


Figure 7.18 Operational Amplifier Voltage Follower Circuit

The MSS apparatus implemented the simple I/O mode for the digital I/O operations required in the control system. When operating in the basic I/O mode the digital subsystem of the PC-30GA takes on the following characteristics:

- The digital I/O section comprises of four ports, two 8-bit ports (A and B) and two 4-bit ports (the upper and lower halves of port C)
- Any of the ports can operate as either an output port or an input port but not as both.
- Ports-that are configured as inputs reflect the digital inputs on the port when read. Ports that are configured as outputs are set and latched to the value most recently written to t he port. The bit definitions for the three ports are given in Table 7.1

PORT	**BIT DEFINITION**							
	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
A	**A7**	**A6**	**A5**	**A4**	**A3**	**A2**	**A1**	**A0**
B	**B7**	**B6**	**B5**	**B4**	**B3**	**B2**	**B1**	**B0**
C	**C7**	**C6**	**C5**	**C4**	**C3**	**C2**	**C1**	**C0**

Table 7.1 Bit Definitions for the three 8-bit ports

Microsoft Visual Basic 6 (VB6) was used to communicate with the PC-30GA card which is controlled via a library of high level functions stored in the dynamic link library, *edr32.dll.* This dynamic link library is supported by the Eagle EDR Software Developers Kit (SDK). The functions required for the control of the digital subsystem of the PC-30GA card are listed in Table7.2. The functions are implemented using the function calls to the edr32.dll library that were provided with the EDR SDK in the Visual Basic code module, edr32. bas. A listing of the functions calls contained the edr32.bas module is presented in Appendix D.

DDL FUNCTION	USAGE
EDR_ValidDIOPortConfig	Validates a port configuration for a specific board type.
EDR_DIOConfigurePort	Sets mode and direction of a port.
EDR_DIOPortInput	Reads the data from an entire port.
EDR_DIOLineInput	Reads the data from a specific line of a specific port.
EDR_DIOPortOutput	Reads the data from an entire port.
EDR_DIOLineOutput	Reads the data from a specific line of a specific port.

Table 7.2 High level Functions used to Control the Digital Portion of the PC-30GA

The three ports of the, digital portion of the PC-30GA must be configured before they m be used for digital 1/0 transactions. The configuration process involves two steps requiring calls to the EDR_ ValidDIOPortConfig library function and the EDR_DIOConfigurePort function respectively.

The EDR_ValedDloPortConfig function is a validation function that returns a value indicating whether the desired configuration settings of a port are valid for an I/O card of the specified type. The code to implement the call is presented as follows:

> Declare Function EDR_ValidDIOPortGonfig Lib ‘’EDR32.DLL’’ (ByVal **boardtype** As Long, Byval **port** As Long, ByVal **tmode** As Long, ByVal **io** As Long).

7.8.3 User Interface Development and Control Algorithms

The operator had to be able to access and see the results of the software coded algorithms that controlled and monitored different processes of the MSS apparatus. To this effect, a user interface between the PC and the operator was developed. To develop a user-friendly interface, the developed interface should be visual. The coded control algorithms and the user interface were implemented using Visual Basic 6.0 programming language. Visual Basic 6.0 provided a platform whereby a user interface could be developed efficiently. This standardized the MSS apparatus’ programming language.

To allow the operator to have access to different control programmes of systems / parts mechanisms of the MSS apparatus at any time, a pyramid, hierarchical user interface was developed. A modular design approach was used to develop the user interface. On running the control programme of the MSS apparatus, the main control programme used control buttons to move to other control sub-programmes. Each sub-programme had a control button that could control the subsystem of the MSS apparatus (see Figure 7.19).

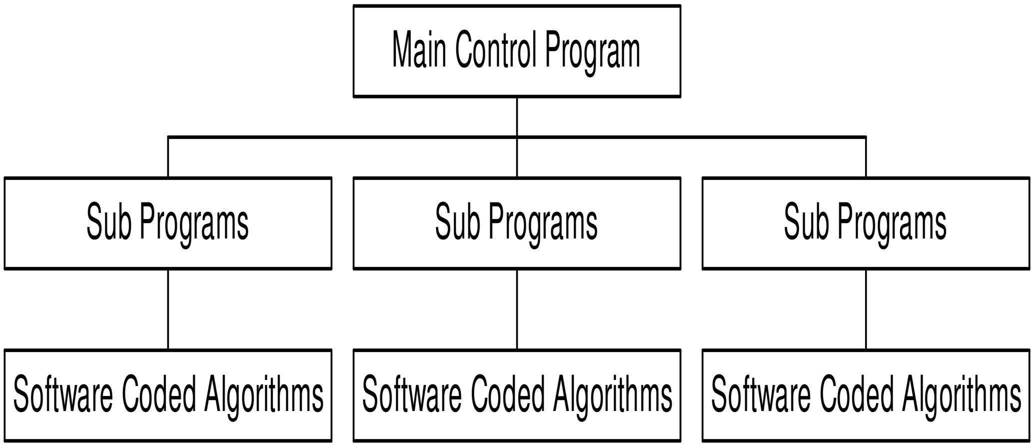


Figure 7.19 Hierarchical Structure of the Main Control Programme

7.8.4 The Main Control Programme

The requirement on the main control programme was to allow the operator to navigate the different control sub-programmes with ease. The main control programme gave the operator the following choices that invoked sub-programmes that controlled different mechanisms or systems of the MSS apparatus:

- Conveyor Motor Control.
- Pallet Position Control.
- Bar Code and Scanner Control.

When the operator had selected the sub-programme desired, by clicking on the relevant command button, the main control programme run in the background. This ensured that interface board initialisation was not lost. However, closing a sub-programme would result in the sub-programme being unloaded. This ensured a smooth and synchronized control of the MSS apparatus.

The software code that was implemented for this purpose was:
Unload [name of the form to be unloaded]. This command, Unload, would unload the programme, the name of which followed after it. The same command was implemented when the Exit Programme command button was pressed. The main control programme was used to structure the control programmes efficiently, and to initialise the PC30GA interface board. Moreover, the each digital I/O port had to be set as either output. This was implemented in the main control programmes because it was used to navigate between the different control sub-programmes. The code implemented to initialize and set the PC306A interface board was embedded in the procedure *Private Sub CheckBoard* (). The code started first by setting the board handle (bh) of the PC30GA interface card as 1. This corresponded to the number of the first interface card manufactured by Eagle Technology inserted in the ISA slots. This number was used by the PC to communicate with the interface card.. Thereafter, the code:

EDR_GetBoardType(bh, bt)
EDR_StrBoardType bt, bs

was used to determine the board type *(bt)* and to set name of the board type *(bs)* of the interface card. The board type was then to determine the number of digital O/I ports, the number of analogue to digital inputs channels and the number of analogue output lines using the code:

EDR-NumDIOPorts(bt)
EDR-NumADInputs(bt, EDR-SINGLEENDED)
EDRChanListLen 0, 15
EDR-NumD,40utputs(bt)
EDR-SetDAOutRange 1,0 EDR-R,4NGEIOB

The digital I/O ports were then configured. Port A was configured as an input port, while Ports B and C were configured as output ports. Finally, the *Enable* properties of all the timers implemented by the all the control programmes were set to false on invoking any programme. This was to ensure that the code embedded in the timers was not executed when the control programmes were being invoked.

7.9 Chapter Summary

The chapter presented the layout and positions of sensors implemented on the MSS apparatus to provide real-time feedback information and the methodology used to control the system. The electronic circuits of different sensors implemented in the system and their working principles were presented. A brief review of signal conditioning as well as data acquisition and analysis was also given. The chapter concluded by describing the development of the software coded algorithms implemented in control the MSS apparatus as well as interface board used.

Chapter 8

8 PERFOMANCE ANALYSIS OF THE MSS APPARATUS

8.1 Introduction

This chapter presents the performance analysis of the MSS apparatus conducted and the discussion thereof. An analysis of the operation times of each individual mechanism/system determines the overall processing time of the MSS apparatus thereby highlighting the systems that may require optimisation.

The overall performance analysis of the Mechatronic Sensory System (MSS) apparatus was dependent on the performances of the individual mechanisms and systems that constituted the MSS apparatus. The performances of the individual mechanisms were:

- The efficiency of the conveyor system in transporting the pallet throughout the conveyor segments.
- The efficiency of the sensors in the operation of the MSS apparatus.
- The efficiency of the bar code and scanner system to scan the metal billet of the system.

8.2 Performance Analysis of the Conveyor System

The functions of the roller conveyors of the MSS apparatus were to: act as platform for transporting the workpiece on the CIM cell through a pallet of dimensions 200 x 200 x 5 millimetres. The pallet ensured that the workpiece is conveniently transported through the various CIM cell components and moreover, the pallet protected the workpiece from damage during transportation.

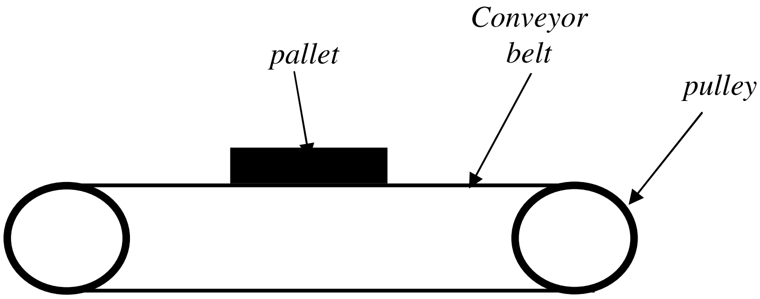


Figure 8.1 Conveyor System of the MSS Apparatus

The belt conveyor system is basically an endless strap stretched between two pulleys as shown in Figure 8.1. This basic arrangement is suitable only for very short distances and low outputs. With longer distances it is necessary to support the conveyor belt at regular intervals to prevent undue sagging, and to reduce the spillage of material that may occur if the belt does not run truly. These two requirements are usually met by idlers that support the belt. The driving pulley relies on the friction between the pulley and the belt to provide the drive to the belt. The lower strand tension depends on the belt sufficiently tight all along its length for some tension to be remaining at the point just after the belt leaves the driving pulley. If the two tensions in the belt at the driving pulley are P_1 and P_2, with P_1 the larger tension in the top strand, the limiting ratio of the tensions when slip is about to occur is given by:

$$\frac{P_1}{P_2} = e^{\mu\theta} \tag{8.1}$$

or

$$\log_{10}\frac{P_1}{P_2} = 0.434\mu\theta \tag{8.2}$$

where μ is the coefficient of friction between the pulley and the belt, and angle θ is the angle of wrap, as shown in Figure 8.2.

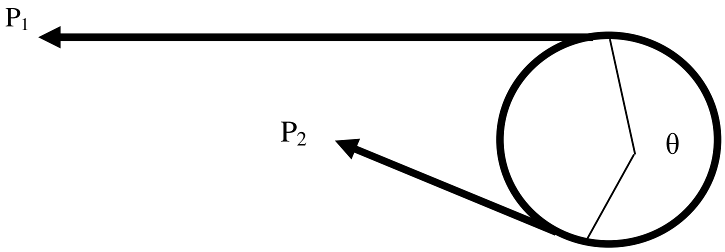


Figure 8.2 Driving Pulley Belt Tension

8.2.1 Factors Affecting the use of Conveyor Belts

- A straight line plan is usually required, although small deviations of a few degrees are possible. If the line of the conveyor must be angled, it is often necessary to use separate conveyors.
- The angle of inclination of the conveyor is limited but the friction of the material to about 25^0,
- The carrying capacity of the belt depends on how the material can be placed on the belt width.

The carrying capacity of the conveyor is given by the equation

$$T = abv \tag{8.3}$$

where T is the carrying capacity, a is the average cross-sectional area of the material, b is the bulk density, and v is the speed of the conveyor belt.

The conveyor system of the MSS apparatus was responsible for the accurate delivery of the workpiece on the pallet to the various CIM cell components for processing and/or inspection. The conveyor system was designed to have the capability of reversing the direction of travel of the pallet. This ensured high degree of flexibility with respect to the material handling capability of the MSS apparatus.

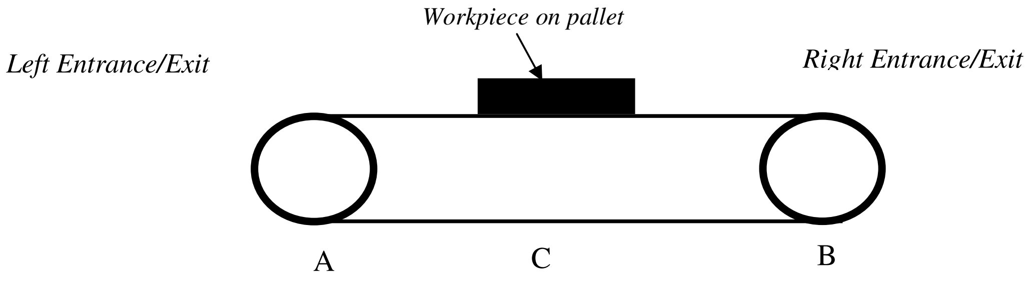


Figure 8.3 Conveyor System indicating various Pallet Positions

For the conveyor system to be effectively reversed, both pulley A and B (Figure 8.3) should experience drive. The design of the conveyor system comprised a timing belt gearing system that provided positive drive to both the left and right pulleys as shown in Figure 8.3. The conveyor system was analysed to determine the requirements of a motor that could be used to power the system through the timing belt arrangement.

The analyses investigated the torque requirements due to frictional resistance of the load at constant speed and optimised the motion profile of the system in respect to the accelerating and decelerating torques required by the motor.

The design parameters used in these analyses are tabulated below.

DESIGN PARAMETER DESCRIPTION	SYMBOL	VALUE
Maximum Conveyor Load	m_L	50 kg
Length of travel of conveyor	L	2000 mm
Mass of the conveyor Pulley	m_p	2 kg
Diameter of conveyor Pulleys	D_p	100 mm
Timing Belt Pulley Mass	m_{tp}	1 kg
Timing Belt Pulley Diameter	D_{tp}	80 mm
Coefficient of friction (pallet/surface)	μ_{ps}	0.357
Conveyor Reduction Ratio	1 : 1	

Table 8.1 Corresponding Symbols and values for the conveyor system parameters

8.2.2 Static Analysis

The static analysis of the conveyor system is concerned with the determination of the drive torque required by the system's drive to move the workpiece at constant velocity along the conveyor. The drive torque must overcome the resistance caused by the frictional interaction between the pallet/workpiece and the conveyor. The model for the system neglects the area under the conveyor system and assumes that the frictional load is derived entirely by the conveyor rollers surface and the workpiece pallet (Figure 8.4).

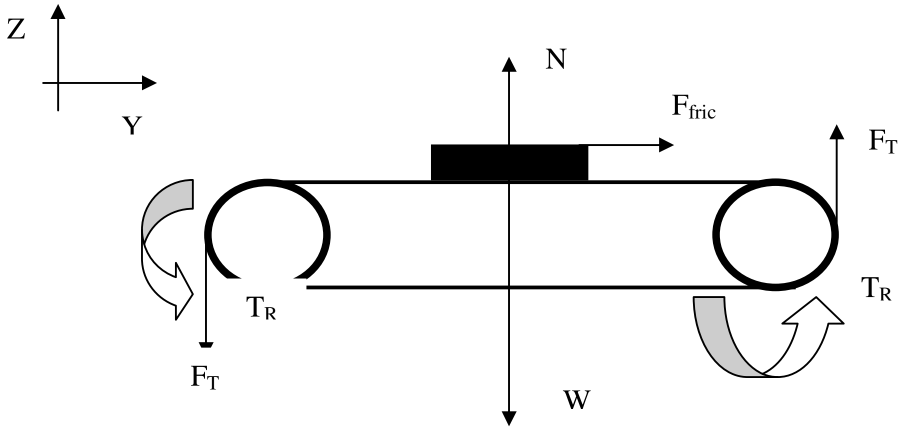


Figure 8.4 Model of Static characteristics of the Conveyor System

Consider the forces acting in the Y direction;

$$\Sigma \quad F_Y = 0 \quad : \quad -2F_T + F_{fric} = 0 \tag{8.4}$$

Since $F_{fric} = \mu_{ps} N$ and $N = \mu_{ps} m_L g$, equation 8.1 can be arranged to isolate F_T.

$$\therefore F_T = 1/2\mu_{ps} m_L g \tag{8.5}$$

An expression for the driving torque required to overcome the frictional resistance can now be derived and evaluated.

$$T_R = F_T D_p/2 = 1/4\mu_{ps} m_L g = 4.57\ Nm \tag{8.6}$$

$$T_R \approx 5\ Nm$$

The drive motor for the conveyor system must therefore be able to supply a constant driving torque of 5 Nm to the conveyor system in order to maintain a constant velocity movement of the workpiece against the frictional load.

8.2.3 Dynamic Analysis

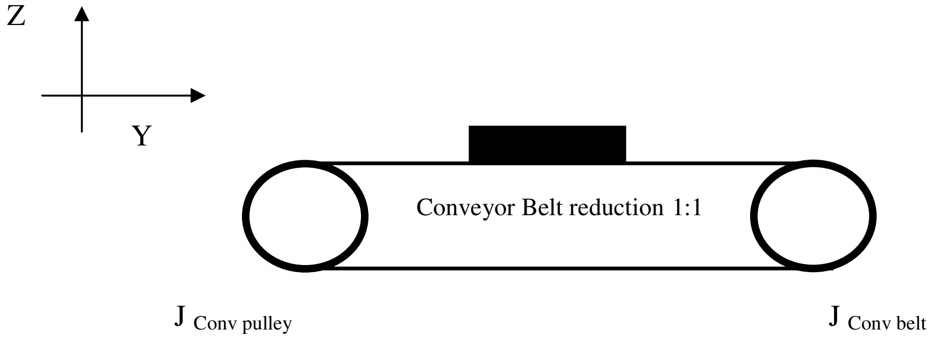


Figure 8.5 Model of Dynamic characteristics of the Conveyor System

The drive motor for the conveyor system experiences an inertia loading effect due to acceleration and deceleration of the workpiece as it stops and starts from different positions along the CIM cell. This analysis calculates the inertia torque required by the motor to accelerate (start) and decelerate (stop) the workpiece. The model considers the motion of the workpiece along the conveyor belt as it was brought through the various equipment within the CIM cell. The model is used to investigate the dynamic loading of the system that includes the effects of additional inertia loads (Figure 8.5).

An expression for the required acceleration torque (T_{req}) in terms of the total system inertia (J_{sys}) and the angular acceleration of the drive motor (ε) can be determined using Euler's Laws.

The procedure used to determine the performance of the roller conveyors when delivering the workpiece throughout the MSS apparatus and the CIM cell was as follows:

- The roller conveyors were made to deliver the pallets with different workpiece sizes and loads by moving the roller conveyor assembly around the CIM cell.
- Proper mating of the modules of the roller conveyor was then tested,
- The state of LDR sensor monitoring the presence of the pallet in the conveyor and to check whether it was activated or not.
- The total time to move the pallet throughout all the CIM cell components was recorded for each run.

The pallet on the conveyor can be modelled as a Differential Algebraic Equation (DAE) as shown in Figure 8.6.

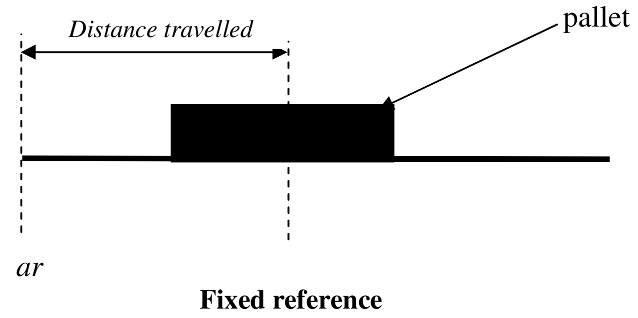


Figure 8.6 Fixed Reference Point

Although a number of factors can have an input on the displacement of the pallets, the following modelling assumptions are made:

- The velocity of the conveyor belt (and thus of the pallets on the belt), is controlled by the torque applied to the motor of the conveyor belt.
- A pallet, together with its load of the workpiece, is assumed to have a fixed mass, which is too small to affect the velocity of the belt in a substantial manner.
- The conveyor belt is equipped with sensors, which are triggered by the movement of the fixed reference point of the pallet.

To analyse the operation of the conveyor, the following parameters need to be specified:

λ = the nominal arrival rate of pallets on the conveyor belt,
v = the velocity of the conveyor belt,
E$[w]$ = the expected value of the window size,
Var$[w]$ = the variance of a window size,
$\mathring{U}$ = the desired utilisation of the conveyor belt line.

From these, the following relations are developed:

$$W_0 = \frac{\rho_0^2 + \lambda_0^2 Var[w]/v^2}{2\lambda_0(1-\rho_0)} + \frac{1}{\mu_0} \tag{8.7}$$

where the λ_0 is the arrival rate of the pallet on the conveyor and ρ_0 is the traffic intensity.

A more realistic analysis of conveyor operation is the environment in which pallets arrive at a constant inter-arrival time T. The upstream environment can in this case be described by a buffer which outputs pallets at a constant inter-arrival time of T time-units in order to avoid a deadlock in the environment. If the conveyor belt accelerates to speed v_{max}, abstracting from the start-up noise, the system can be shown as below:

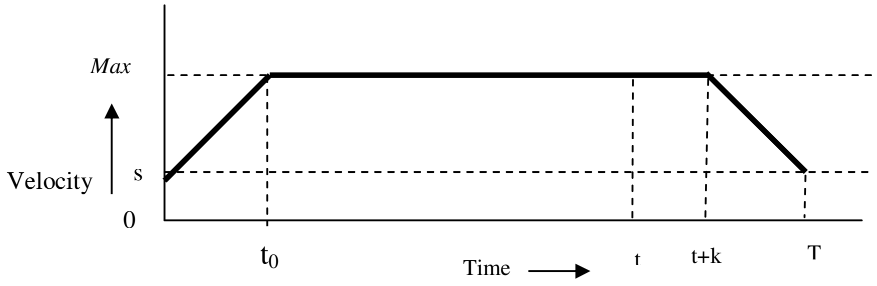


Figure 8.7 Velocity-Time Diagram after Stabilising

If the conveyor belt cannot be accelerated to v_{max}, due to the small delay k and through the interval T. This brings about the problem that the speed of the pallet that arrives next is highly dependent on the speed of the conveyor belt had when the previous pallet was delivered. The inter-arrival time T in combination with the delay time k will cause the belt to be decelerated to a velocity greater than zero before a new pallet arrives as shown in Figure 8.8.

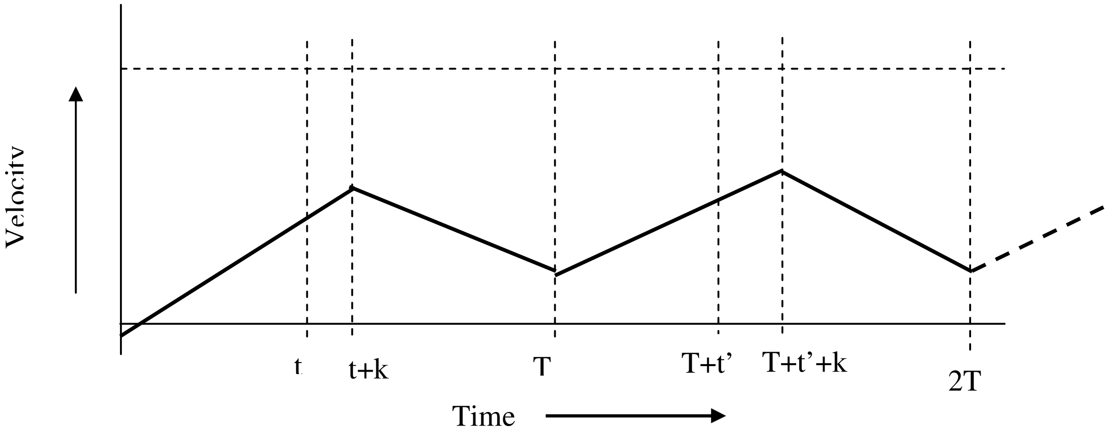


Figure 8.8 Inter-arrival time T in combination with delay time *k*

The procedure used to determine the performance of the roller conveyors during the operation of the MSS apparatus was as follows:

i) The modular roller conveyors were made to deliver the pallets with different loads to the entrance/exit of the constituent conveyor section.

ii) Proper interaction of the DC servomotor of the conveyor system was then tested.

iii) The state of the LDR sensor monitoring the presence of the pallet was then test for activation or not.

iv) The total time to move the pallet between each segment conveyor of the MSS apparatus was then recorded.

v) The state of the LDR sensor monitoring the movement of the pallet's entrance and exit of the conveyor segment was then test for activation or not.

8.3 Determining Conveyor Efficiency

Table 8.2 (a) and (b) presents the results determining the modular conveyors' efficiency in moving the pallets. The average time taken to deliver a part (with a maximum weight of 0.5 kg) on a pallet through a modular conveyor was 6.5 seconds, while the average time taken to deliver a part (with a maximum weight of 0.125 kg) on a pallet through a modular conveyor was 4.5 seconds. All the sensors related to the modular conveyors were instantly activated as required.

Conveyor Module	Times for Max. Load (sec)	Times for Min. Load (sec)
1	6.6	4.4
2	5.9	4.6
3	6.4	4.5
4	6.7	4.6
5	6.4	4.7
6	6.6	4.3
7	6.8	4.4
8	6.3	4.5
9	6.4	4.6

Table 8.2 (a) Efficiency Test Results of the Modular Conveyor Belt

Conveyor Module	S0	S1	S2
1	Activated	Activated	Activated
2	Activated	Activated	Activated
3	Activated	Activated	Activated
4	Activated	Activated	Activated
5	Activated	Activated	Activated
6	Activated	Activated	Activated
7	Activated	Activated	Activated
8	Activated	Activated	Activated
9	Activated	Activated	Activated

Table 8.2 (b) Activation of Sensors

As the conveyor segments are not equal in size, all conveyor segments were analysed as well as the operation of their sensor pairs. As the width of the conveyor is quite larger than the width of the pallet, the pallet movement on the conveyor was problematic, and thus a guide rail was built to alleviate this problem as shown in Figure 8.10.

Figure 8.10 Pallet with guide rail positioned on the conveyor

Conveyor Segment	Run	Times for Max. Load (sec)	Times for Min. Load (sec)	Activation of the sensors (S11)	Activation of the sensors (S12)
1	1	6.5	4.5	Activated	Activated
	2	6.0	4.4	Activated	Activated
	3	6.3	4.3	Activated	Activated
	4	6.8	4.5	Activated	Activated
	5	6.6	4.4	Activated	Activated
	6	6.7	4.7	Activated	Activated
	7	6.4	4.5	Activated	Activated
	8	6.5	4.6	Activated	Activated
	9	6.4	4.8	Activated	Activated
	10	6.6	4.5	Activated	Activated
2	**Run**	**Times for Max. Load (sec)**	**Times for Min. Load (sec)**	**Activation of the sensors (S21)**	**Activation of the sensors (S22)**
	1	5.8	4.4	Activated	Activated
	2	5.6	4.3	Activated	Activated
	3	5.5	4.2	Activated	Activated
	4	5.7	4.4	Activated	Activated
	5	5.7	4.2	Activated	Activated
	6	5.8	4.4	Activated	Activated
	7	5.7	4.3	Activated	Activated
	8	5.6	4.2	Activated	Activated
	9	5.8	4.4	Activated	Actiated
	10	5.8	4.1	Activated	Activated

Table 8.3 [A] Efficiency Test Results for Conveyor Segment 1 & 2 and Sensor Activation

Conveyor Segment	Run	Times for Max. Load (sec)	Times for Min. Load (sec)	Activation of the sensors (S31)	Activation of the sensors (S32)
3	1	5.8	4.3	Activated	Activated
	2	5.7	4.3	Activated	Activated
	3	5.6	4.3	Activated	Activated
	4	5.6	4.3	Activated	Activated
	5	5.8	4.2	Activated	Activated
	6	5.9	4.3	Activated	Activated
	7	5.5	4.4	Activated	Activated
	8	5.6	4.3	Activated	Activated
	9	5.6	4.4	Activated	Activated
	10	5.8	4.2	Activated	Activated
4	**Run**	**Times for Max. Load (sec)**	**Times for Min. Load (sec)**	**Activation of the sensors (S41)**	**Activation of the sensors (S42)**
	1	5.7	4.4	Activated	Activated
	2	5.7	4.3	Activated	Activated
	3	5.6	4.2	Activated	Activated
	4	5.6	4.3	Activated	Activated
	5	5.6	4.3	Activated	Activated
	6	5.6	4.4	Activated	Activated
	7	5.7	4.3	Activated	Activated
	8	5.6	4.2	Activated	Activated
	9	5.7	4.3	Activated	Activated
	10	5.7	4.1	Activated	Activated

Table 8.3 [B] Efficiency Test Results for Conveyor Segment 3 & 4 and Sensor Activation

Conveyor Segment	**Run**	**Times for Max. Load (sec)**	**Times for Min. Load (sec)**	**Activation of the sensors (S51)**	**Activation of the sensors (S52)**
5	1	8.5	6.5	Activated	Activated
	2	8.4	6.4	Activated	Activated
	3	8.3	6.3	Activated	Activated
	4	8.8	6.5	Activated	Activated
	5	8.6	6.4	Activated	Activated
	6	8.7	6.7	Activated	Activated
	7	8.4	6.5	Activated	Activated
	8	8.5	6.6	Activated	Activated
	9	8.4	6.8	Activated	Activated
	10	8.6	6.5	Activated	Activated
6	**Run**	**Times for Max. Load (sec)**	**Times for Min. Load (sec)**	**Activation of the sensors (S61)**	**Activation of the sensors (S62)**
	1	5.7	4.4	Activated	Activated
	2	5.6	4.3	Activated	Activated
	3	5.5	4.2	Activated	Activated
	4	5.7	4.4	Activated	Activated
	5	5.7	4.2	Activated	Activated
	6	5.8	4.3	Activated	Activated
	7	5.7	4.3	Activated	Activated
	8	5.6	4.2	Activated	Activated
	9	5.8	4.3	Activated	Activated
	10	5.8	4.1	Activated	Activated

Table 8.3 [C] Efficiency Test Results for Conveyor Segment 5 & 6 and Sensor Activation

Conveyor Segment	**Run**	**Times for Max. Load (sec)**	**Times for Min. Load (sec)**	**Activation of the sensors (S71)**	**Activation of the sensors (S72)**
7	1	6.5	4.5	Activated	Activated
	2	6.4	4.4	Activated	Activated
	3	6.3	4.3	Activated	Activated
	4	6.8	4.5	Activated	Activated
	5	6.6	4.4	Activated	Activated
	6	6.7	4.7	Activated	Activated
	7	6.4	4.5	Activated	Activated
	8	6.5	4.6	Activated	Activated
	9	6.4	4.8	Activated	Activated
	10	6.6	4.5	Activated	Activated
8	**Run**	**Times for Max. Load (sec)**	**Times for Min. Load (sec)**	**Activation of the sensors (S81)**	**Activation of the sensors (S82)**
	1	5.8	4.3	Activated	Activated
	2	5.7	4.3	Activated	Activated
	3	5.6	4.3	Activated	Activated
	4	5.6	4.3	Activated	Activated
	5	5.8	4.2	Activated	Activated
	6	5.7	4.3	Activated	Activated
	7	5.5	4.4	Activated	Activated
	8	5.6	4.3	Activated	Activated
	9	5.6	4.4	Activated	Activated
	10	5.8	4.2	Activated	Activated

Table 8.3 [D] Efficiency Test Results for Conveyor Segment 7 & 8 and Sensor Activation

Conveyor Segment	**Run**	**Times for Max. Load (sec)**	**Times for Min. Load (sec)**	**Activation of the sensors (S91)**	**Activation of the sensors (S92)**
9	1	5.7	4.4	Activated	Activated
	2	5.7	4.3	Activated	Activated
	3	5.6	4.2	Activated	Activated
	4	5.6	4.3	Activated	Activated
	5	5.6	4.3	Activated	Activated
	6	5.6	4.4	Activated	Activated
	7	5.7	4.3	Activated	Activated
	8	5.6	4.2	Activated	Activated
	9	5.7	4.3	Activated	Activated
	10	5.7	4.1	Activated	Activated
10	**Run**	**Times for Max. Load (sec)**	**Times for Min. Load (sec)**	**Activation of the sensors (S101)**	**Activation of the sensors (S102)**
	1	5.8	4.4	Activated	Activated
	2	5.6	4.3	Activated	Activated
	3	5.5	4.2	Activated	Activated
	4	5.7	4.4	Activated	Activated
	5	5.7	4.2	Activated	Activated
	6	5.8	4.4	Activated	Activated
	7	5.7	4.3	Activated	Activated
	8	5.6	4.2	Activated	Activated
	9	5.8	4.4	Activated	Activated
	10	5.8	4.1	Activated	Activated

Table 8.3 [E] Efficiency Test Results for Conveyor Segment 9 & 10 and Sensor Activation

The average times for the pallet with a maximum weight of 0.5 kg and a minimum weight of 0.2 kg to traverse through the 10 conveyor segments as shown in Table 8.4.

Conveyor Segment	Ave. Time For Max. Load (sec)	Ave. Time For Min. Load (sec)
1	6.5	4.5
2	5.7	4.3
3	5.7	4.3
4	5.7	4.3
5	8.5	6.5
6	5.7	4.3
7	6.6	4.5
8	5.6	4.3
9	5.7	4.3
10	5.7	4.3

Table 8.4 Average times for Pallet with a weight moving through Conveyor Segments

CONVEYOR SEGMENT NUMBER	ELAPSED TIME IN SECONDS
1	10
2	9
3	9
4	9
5	62
6	9
7	9
8	9
9	9
10	115

Table 8.5 Time taken by a Pallet to Traverse through all Conveyor Segments

All actions are performed using a series of delays and timers that are based on the average time taken for a pallet to traverse a particular conveyer segment (see table 8.5) plus an added safety margin.

8.4 Performance Analysis of Sensors

A series of emitter-receiver sensor pairs were required to actuate the MSS apparatus in order to move the work piece pallet throughout the modular conveyor segments. The operation of the sensors developed for the MSS apparatus was presented in section 7.1

This section reviews the performance analysis of the sensors pairs throughout the conveyor belt with respect to the precision positioning against each other. The effect of the distance between the emitter and receiver pairs will be discussed as well as the amplitude.

8.4.1 Sensor Position System Error Analysis

The MSS apparatus utilised the emitter-receiver sensor pair switch back system that actuated the modular conveyor motors and monitored the real time position of the pallet along the pallet transport modular conveyors (refer to section 7.2). The feedback system was able to monitor the presence of the pallet at different locations along the modular conveyor sections (Figure 8.12). An infra-red beam operated between the emitter and receiver sensor pair is used to monitor the position of the pallet. The sensor pairs were strategically positioned along the modular conveyor segments to actuate them and to provide real time position of the pallet. The control system algorithm was designed to stop the actuation of the modular conveyor motor if any combination of the symmetric sensor pairs were switched high (refer to Chapter 7.) The performance part of the sensor pair positioning was investigated to determine the relative response in resistance compared to the distances between the sensor pairs.

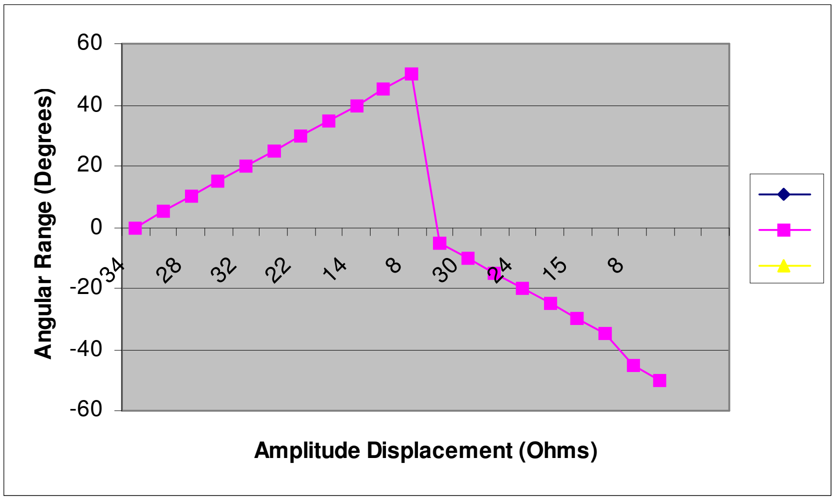


Figure 8.11 Sensor Angle and Amplitude Displacement

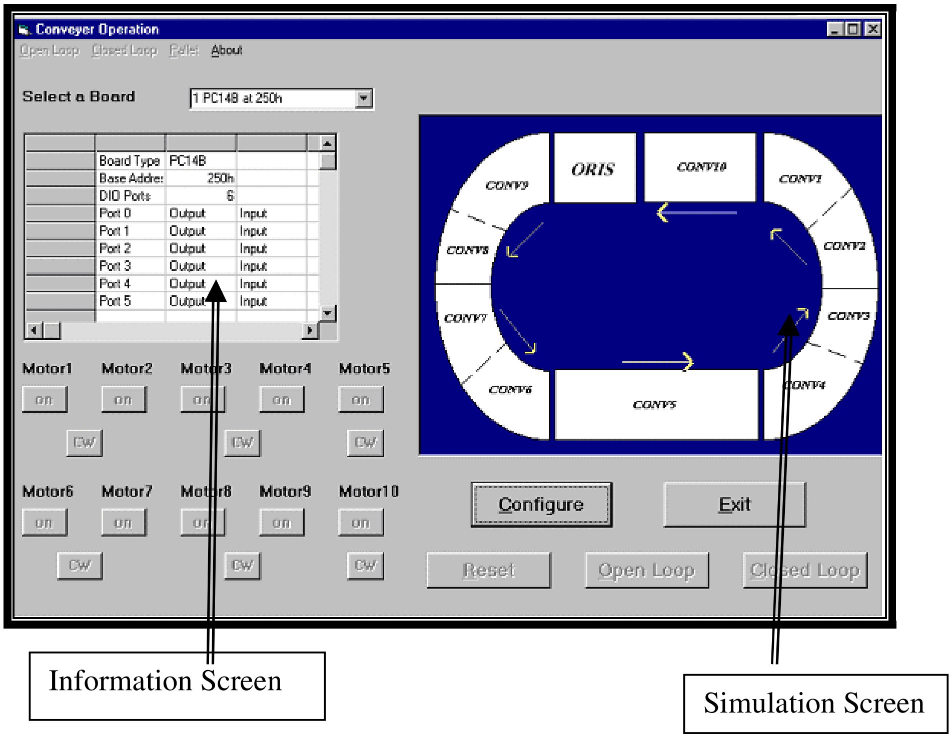
8.5 The Conveyer Control

The controls required under the Conveyor Control sub-programme were:

- Switch the motors ON or OFF
- Drive the motors CLOCKWISE (CW) or COUNTER CLOCKWISE (CCW).

There was positional control required of the pallet and this was achieved through a series of sensors strategically placed along the conveyor system. On start-up the operator is presented with the Conveyer Operation form (see figure 8.12).

This is the main control window of the program that contains all the menus and short cuts for the user to navigate around the program's various options quickly and effectively. For each port to be configured for input or output, the ''Select a Board'' combo box allows the user to select the correct Eagle Technology card if more than one has been installed. If only one is available the program will automatically set this as the default card. A simulation of the conveyer set-up is also shown in its neutral state on the Simulation Screen. The arrows on the simulation screen show the default direction that a pallet would follow if a motor was to be switched on. The ''Exit'' button allows the user to exit the program at any stage of operation. It will switch off all the motors and reset to their default directions before closing the program.



Select a Board: 1 PC14B at 250h

Board Type	PC14B	
Base Addre	250h	
DIO Ports	6	
Port 0	Output	Input
Port 1	Output	Input
Port 2	Output	Input
Port 3	Output	Input
Port 4	Output	Input
Port 5	Output	Input

Information Screen

Simulation Screen

Figure 8.12 Opening Screen of Conveyer Control Sub Programme

A number of features have been included in this sub-programme. Manual Control allows for individual motors to be turned on and off and their directions changed in real time. Open Loop Control will enable a pallet to travel to present destinations using time delays. Closed Loop Control uses feedback from the sensors to determine the path of the pallet to its destination. The movement of all pallets as well as the motors that are activated and the direction of conveyer movement can be visualised on a real time simulation.

The Simulation Screen below (Figure 8.13) shows the conveyer set-up in its neutral state without the arrows depicting the direction that a pallet would follow if a motor where to be switched on.

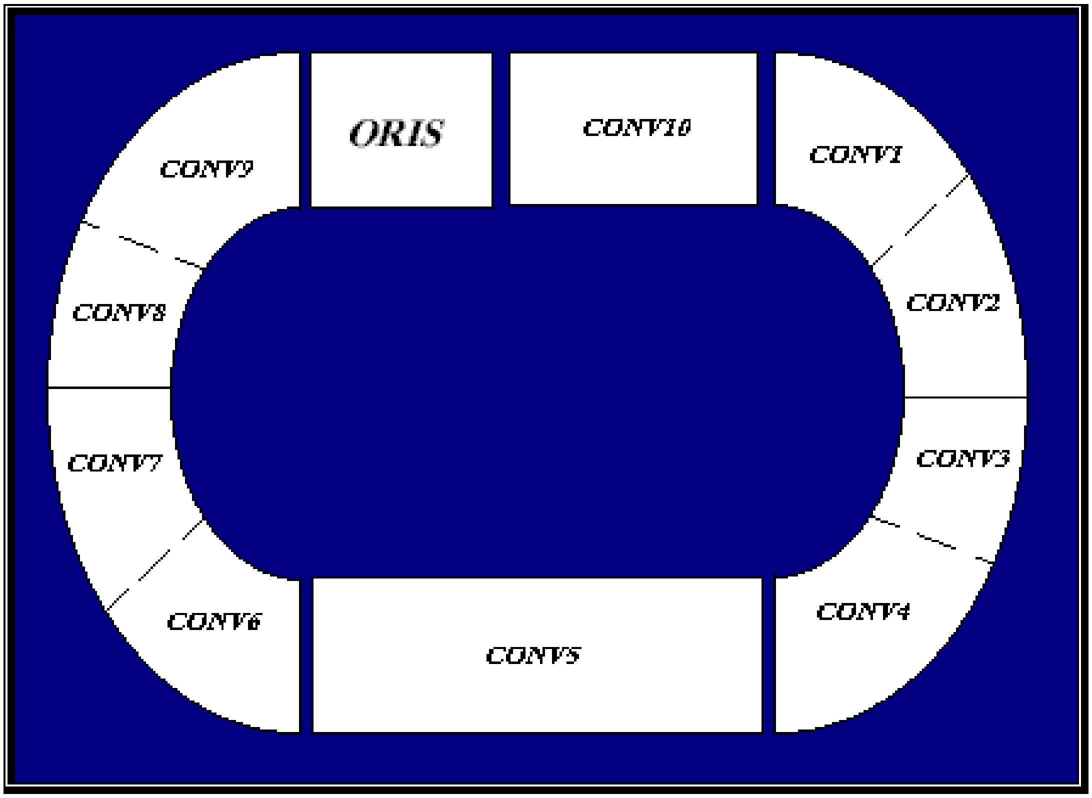
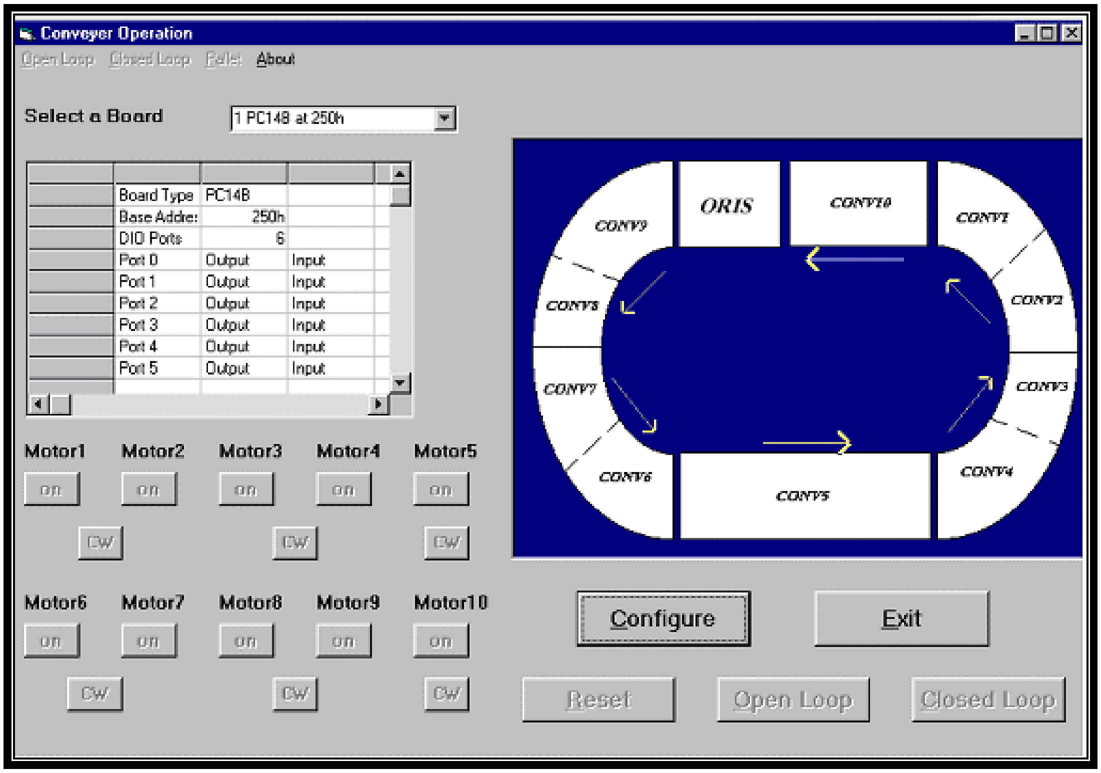


Figure 8.13 Simulation Screen

Pressing the ''Configure'' button enable all the menus and buttons rendering the conveyer ready for operation (see Figure 8.14). Port 0 and port 1 are configured for outputs and port 2 to port 5 are enabled for inputs. The Information Screen shows the individual states of all the pins. The pins have been divided into six ports of eight lines each (see table 8.5). For port 0 and port 1 a =5V signal from the sensors (e.g. a pallet blocking the sensors) will appear as a ''1'' whereas a card ground signal would appear as a 0.



Select a Board: 1 PC148 at 250h

Board Type	PC14B	
Base Addr:	250h	
DIO Ports	6	
Port 0	Output	Input
Port 1	Output	Input
Port 2	Output	Input
Port 3	Output	Input
Port 4	Output	Input
Port 5	Output	Input

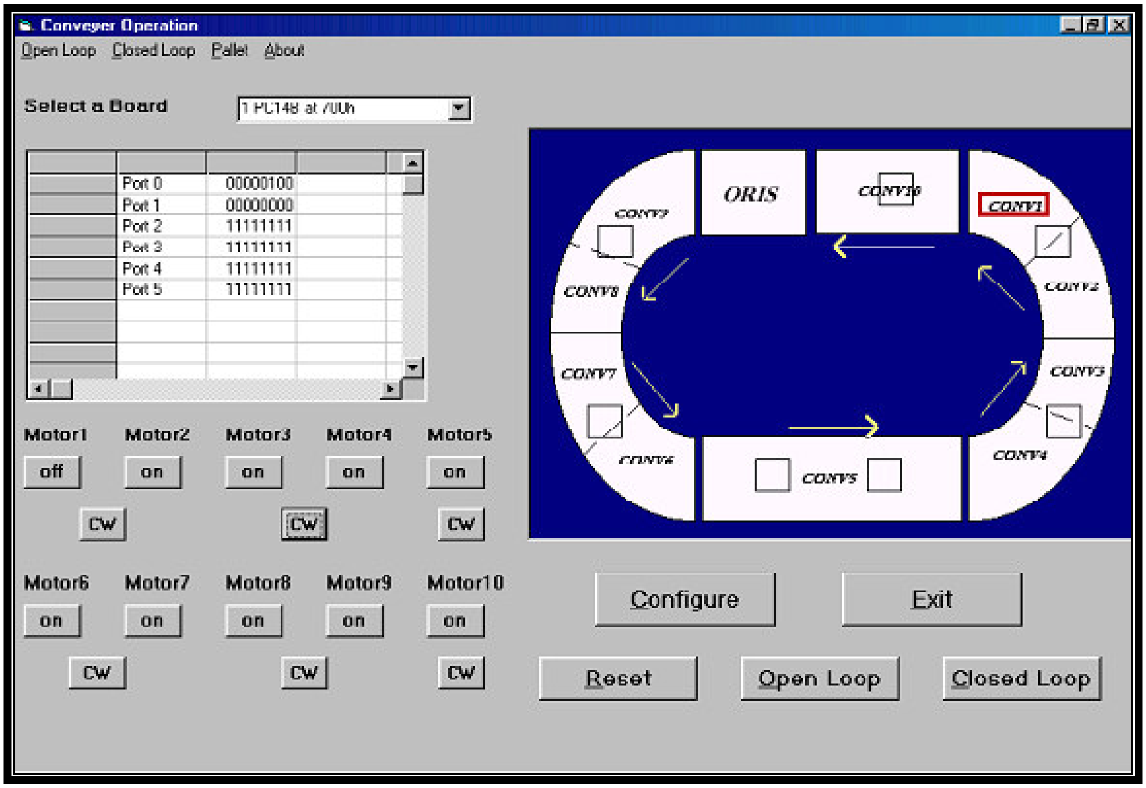
Figure 8.14 Pressing the Configure Button

PORT 0	LINE 8 PIN 8	LINE 7 PIN 7	LINE 6 PIN 6	LINE 5 PIN 5	LINE 4 PIN 4	LINE 3 PIN 3	LINE 2 PIN 2	LINE 1 PIN 1
PORT 1	LINE 8 PIN 16	LINE 7 PIN 15	LINE 6 PIN 14	LINE 5 PIN 13	LINE 4 PIN 12	LINE 3 PIN 11	LINE 2 PIN 10	LINE 1 PIN 9
PORT 2	LINE 8 PIN 24	LINE 7 PIN 23	LINE 6 PIN 22	LINE 5 PIN 21	LINE 4 PIN 20	LINE 3 PIN 19	LINE 2 PIN 18	LINE 1 PIN 17
PORT 3	LINE 8 PIN 32	LINE 7 PIN 31	LINE 6 PIN 30	LINE 5 PIN 29	LINE 4 PIN 28	LINE 3 PIN 27	LINE 2 PIN 26	LINE 1 PIN 25
PORT 4	LINE 8 PIN 40	LINE 7 PIN 39	LINE 6 PIN 38	LINE 5 PIN 37	LINE 4 PIN 36	LINE 3 PIN 35	LINE 2 PIN 34	LINE 1 PIN 33
PORT 5	LINE 8 PIN 48	LINE 7 PIN 47	LINE 6 PIN 46	LINE 5 PIN 45	LINE 4 PIN 44	LINE 3 PIN 43	LINE 2 PIN 42	LINE 1 PIN 41

Table 8.5 Explanation of Information Screen Output after Configuration

8.5.1 Manual Control

This option gives operator complete control of the conveyer set-up in real-time. Individual motors can be switched ON or OFF and their respective directions changed by pressing control buttons. The motor numbering does coincide with the conveyer numbering. Thus clicking on the ''ON button of motor five will switch on conveyer segment five in a default direction corresponding to the pallet moving in al counter-clockwise direction. The manual control button's labels state the action that will occur should a particular button be clicked on. Thus on configuration, the ''ON'' buttons are enabled since no motors require being switched off. By pressing an ''ON'' button a motor is switched on and the corresponding ''OFF'' button for that motor is displayed (ref Figure 8.15).



Select a Board: 1 PC148 at 700h

Port 0	00000100
Port 1	00000000
Port 2	11111111
Port 3	11111111
Port 4	11111111
Port 5	11111111

Figure 8.15 Manual Control Operation

8.5.1.1 Closed Loop Control

The Closed Loop Control (CLC) offers four pre-programmed routes for the transportation of a pallet around the conveyer. The operation uses feedback from the twenty five infra-red sensors mounted around the track to switch on or of the necessary conveyer segment so that the task is performed in the most efficient manner. The sensors also keep the Simulation Screen updated with the pallets movements.

The following buttons (ref Table 8.6) may also be activated through the 'Closed Loop'' menu command situated at the top of the Conveyor Control Form:

Button Label	Menu Label	Short cut	Description
Dock to ORIS CCW	Dck-ORIS-CCW	F1	Transports pallet from docking position to ORIS counter clockwise
Dock to ORIS CW	Dck-ORIS-CW	F2	Transports pallet from docking position to ORIS clockwise
ORIS to Dock CCW	ORIS-Dck-CCW	F3	Transports pallet from ORIS to docking position counter clockwise
ORIS to Dock CW	ORIS-Dck-CW	F4	Transports pallet from ORIS to docking position clockwise

Table 8.6 Path for Closed Loop Control

The flowchart representing the structure of the programme (see Figure 8.16) for the transportation of a pallet from the docking position to the ORIS/AVIS in a clockwise direction as shown as F2 in the shortcuts of the Closed Loop control.

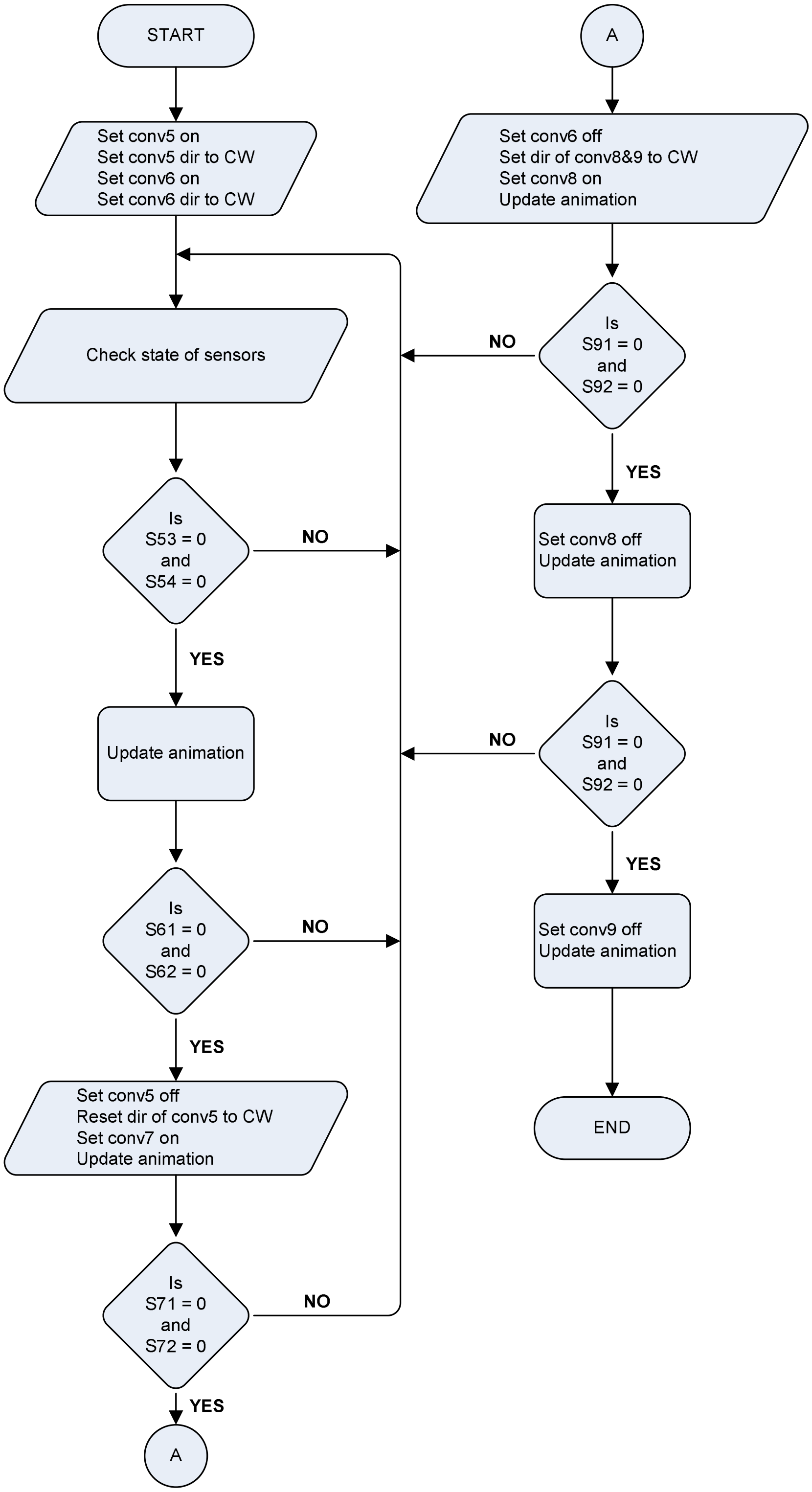


Figure 8.16 Flowchart showing ''Dock to ORIS/AVIS CW''

8.5.1.2 Open Loop Control

The Open Loop Control (OLC) feature is a back-up system should the CLC feature fail. Such failure could be the result of broken or misaligned light sensors, an irregular work piece larger than 300mm in width or an environment that scatters the infrared beam of the light sensors. The OLC feature performs exactly the same pre-programmed transportation movements as the CLC command except that there is no corrective feedback from the sensors should something go wrong. The OLC form can be activated by pressing the ''Open Loop'' button. The OLC will depict buttons of constituent CIM cell components as shown in Figure 8.17.

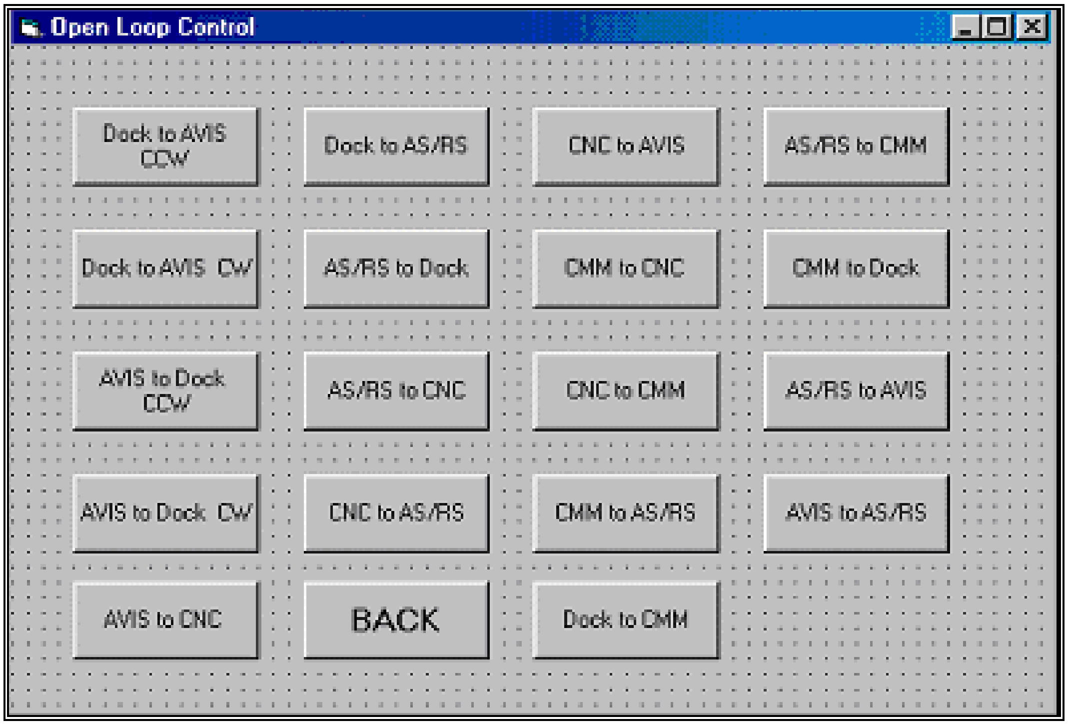


Figure 8.17 Open Loop Control Form

Button Label	Menu Label	Short-Cut	Description
Dock to ORIS CCW	Dck-ORIS-CCW	Crl-+D	Transports pallet from docking position to ORIS counter clockwise
Dock to ORIS CW	Dck-ORIS-CW	Crl-+E	Transports pallet from docking position to ORIS clockwise
ORIS to Dock CCW	ORIS-Dck-CCW	Crl-+O	Transports pallet from ORIS to docking position counter clockwise
ORIS to Dock CW	ORIS-Dck-CW	Crl-+P	Transports pallet from ORIS to docking position clockwise

Table 8.7 Paths for Open Loop Control

The Visual Basic 6 control form called Timer Control can be used to execute an event after a specified amount of time. The interval property is used to set this time that can be any number from 0 to 65535 and is measured in milliseconds. The following algorithm (see figure 8.18) shows the event triggered when the *orisdcktim* timer is enabled. This timer is responsible for the open loop transportation of a pallet from the ORIS to docking position in an anti-clockwise direction.

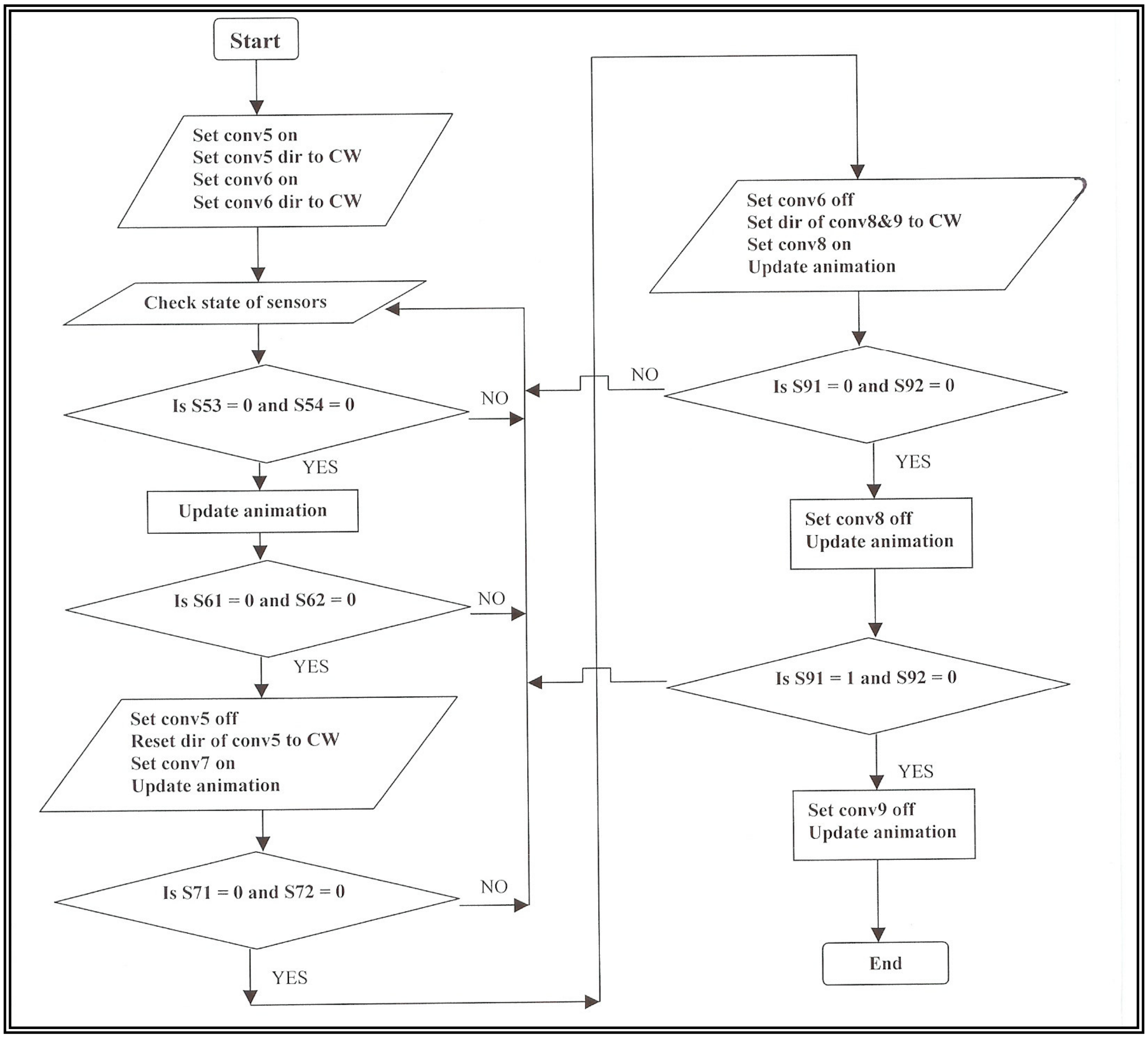


Figure 8.18 Open Loop Algorithm for'' AVIS to Dock CCW"

8.6 The Simulation Screen

The simulation provides an easy check for the user to keep track of all events. It offers a real time update of the state of the motors (on or off), their directions of motion (CW or CCW) and the position of the pallet as it makes its journey around the conveyer segment that is being powered by it. The, direction of pallet movement should a motor be activated is being powered by it. The, direction of pallet movement should a motor be activated is indicated by means of an arrow. By choosing the ''Pallet recognition ON'' command on the Pallet menu or using the short cut Shift + Ins, the simulation will show the pallet movement along the conveyer.

An orange solid pallet is used to show fixed positions (when both sensors in a pair both see the pallet) and a transparent rectangle is seen when the pallet is between sensors on a conveyer segment. Thus the fixed position simulations are of a closed loop nature while the indeterminate state of the pallet between the sensors is open loop.

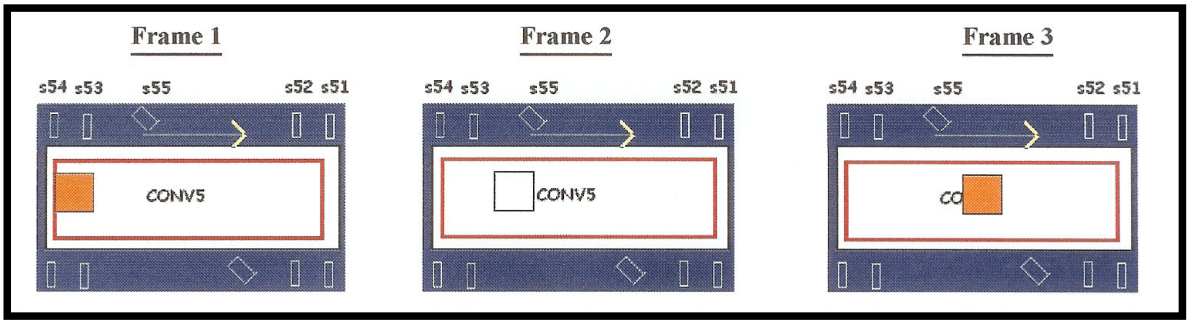
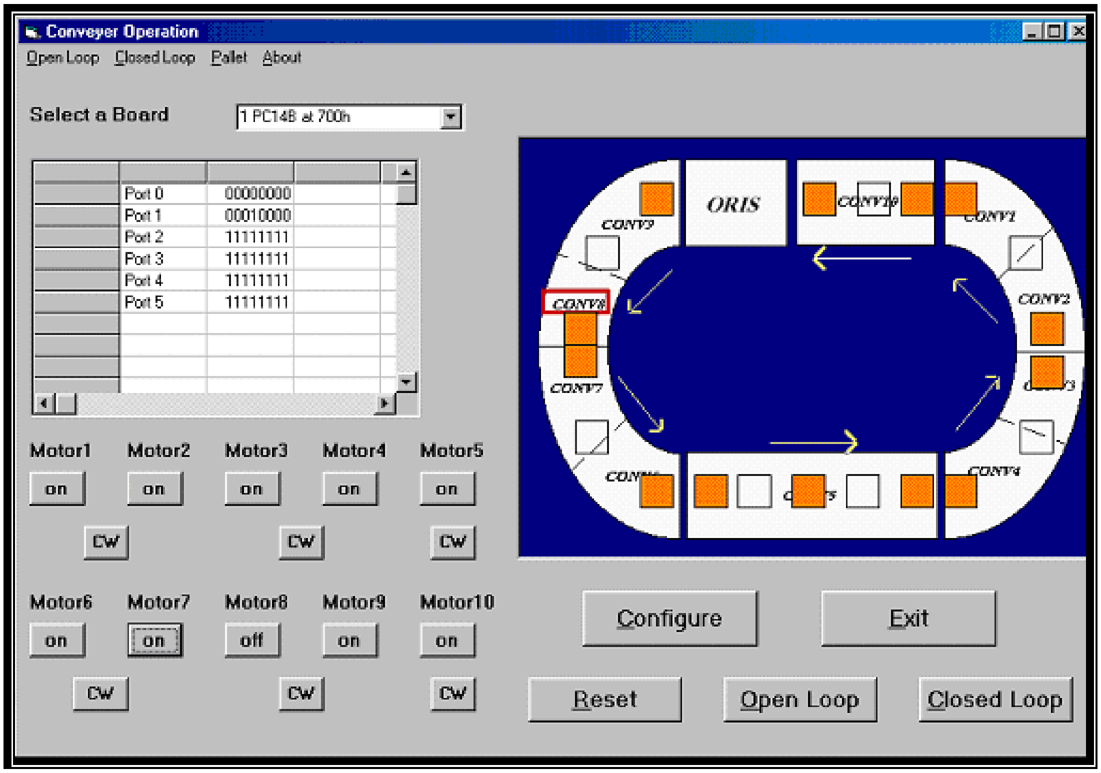


Figure 8.19 Pallet Recognition

Figure 8.19depicts sensors; s51, s52, s53, s54, and s55 mounted on conveyer segment five (5). In Frame 1 the pallet blocks both sensors s54 and s53 causing the 'fixed position pallet' to appear on the screen. This pallet will remain on the screen until both sensors s54 and s53 are unblocked. Due to the direction of the conveyer movement and the last fixed position the pallet is assumed to be in transit between sensors s53 and s55. This is shown on the simulation by the transparent rectangle in Frame 2. Frame 3 shows the fixed position pallet that indicates the arrival of a pallet at the docking position. The Pallet Recognition command can be inactivated by clicking on the ''Pallet recognition OFF'' command on the pallet menu. The pallet position and movement throughout the conveyor segments can be determined on real time and depicted in frames as shown in orange in Figure 8.20



Select a Board: 1 PC148 at 700h

Port 0	00000000
Port 1	00010000
Port 2	11111111
Port 3	11111111
Port 4	11111111
Port 5	11111111

Figure 8.20 Pallet Depiction and Recognition

The feedback information for the conveyer material handling system was collected using the byte array feedback technique. The control module for the conveyer material handling system therefore required fourteen feedback signals to convey the position of the pallet along the conveyer track (ref. Figure 8.21). A list of feedback signals used in the control module for the conveyer system is given in Table 8.8. The conveyer control module was required to generate 12 activation signals used to operate the power electronics developed to control the DC motors.

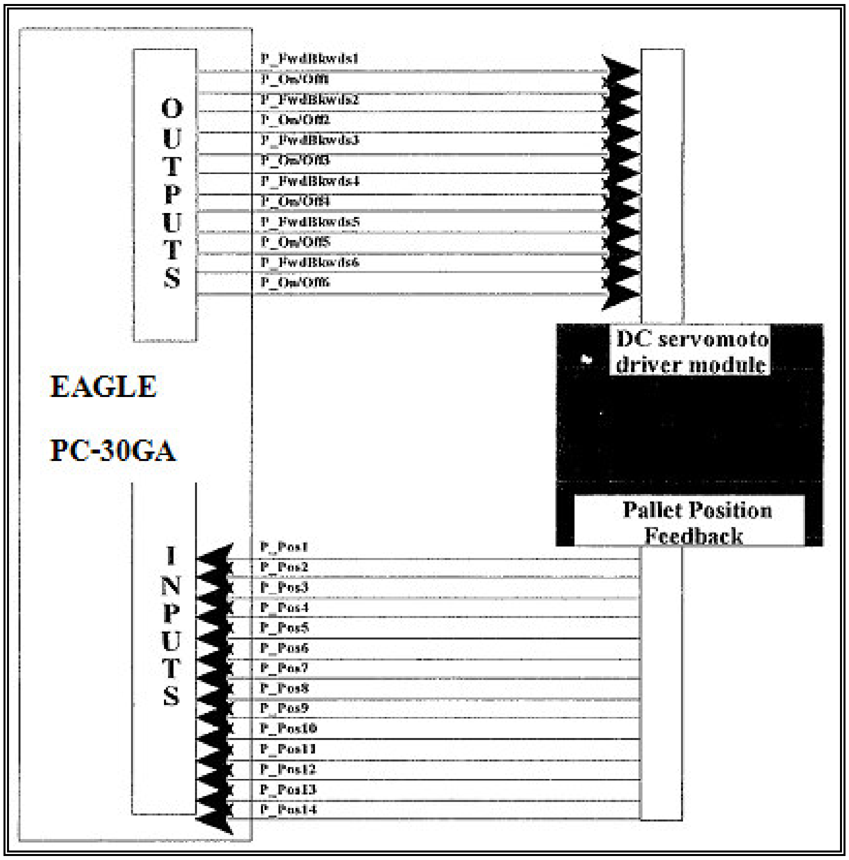


Figure 8.21 A block Diagram depicting the structure of the Conveyor Control Module

Name	Control Function	Port	Line
P_Pos1	Entrance/Exit Conveyor 5 (Motor 8)	A	A0
P_Pos2	Entrance/Exit Conveyor 4 (Motor 6)	A	A1
P_Pos3	Entrance/Exit conveyor 3 (Motor 5) left	A	A2
P_ Pos4	Entrance/exit Conveyor 3 (Motor 5) right	A	A3
P _Pos5	Entrance/Exit Conveyor 2 (Motor 4)	A	A4
P_Pos6	Entrance/Exit Conveyor 1 (Motor 2)	A	A5
P _Pos7	Entrance/Exit Conveyor 6 (Motor 10) right	A	A6
P _Pos8	Entrance/Exit Conveyor 6 (Motor 10) left	A	A7
P _Pos9	Entrance/Exit Conveyor 5 (Motor 9)	A	B0
P _Pos10	Entrance/Exit Conveyor 4 (Motor 7)	A	B1
P _Pos 11	Entrance Exit Conveyor 2 (Motor 3)	A	B2
P _ Pos 12	Entrance Exit Conveyor 1 (Motor 1)	A	B3
P_Pos13	AGV Docking	A	B4
P_Pos14	Robot Pick-up Station	A	B5

Table 8.8 Feedback signals used in the Conveyor Control Module.

8.7 Performance Review of the MSS Apparatus

The overall performance of the MSS apparatus was determined by the sum of individual times taken by each mechanism/system of the MSS Apparatus to perform their required task.

8.8 Chapter Summary

This chapter presented the performance analysis of the MSS apparatus and the discussion thereof. An analysis of the operation times of each individual constituent part of the MSS apparatus was conducted to determine the overall processing time of the MSS apparatus thereby highlighted the areas that may require optimisation.

Chapter 9

9 OPERATION REVIEW OF THE MSS APPARATUS

9.1 Introduction

The MSS apparatus used affordable cost sensors to provide real time information about the states of different positional of the pallet and the actuation of the modular conveyor system. The control of the MSS apparatus was thus a closed loop control system at points where sensors were positioned. Mechatronic sensory feedback was achieved by implementing the correct sensor with the relevant sensory circuitry.

This chapter first presents the positional layout sensors implemented on the MSS apparatus to provide real time feedback information. The MSS apparatus was implemented in a research based Computer Integrated Manufacturing (CIM) cell in the School of Mechanical Engineering at the University of KwaZulu-Natal.

The chapter also presents case studies of the operational procedures adopted by industrial systems similar to the MSS apparatus. The aim of these case studies is to enhance the reader's understanding of the overall function of the MSS apparatus and to highlight the re-configurable nature of the system.

9.2 Implementation of the MSS Apparatus in CIM Environment

This section discusses the implementation of the MSS apparatus in the computer integrated manufacturing (CIM) environment and reviews the characteristics of the apparatus that facilitated its successful integration.

The MSS apparatus was designed as a material handling device that should be implemented to perform work piece transportation on the pallet, determination of pallet position and its movement throughout the conveyor segments within the CIM cell. It was thus essential that the MSS apparatus be able to seamlessly integrate with other existing materials handling systems of the CIM cell.

The MSS apparatus was supported by height-adjustable feet (refer to Figure 9.1) which enabled the fine adjustment of the working height of the modular conveyor system. The height of the modular conveyor system was therefore adjusted to match each conveyor segment in order to transport the pallet and work piece within the CIM Cell.

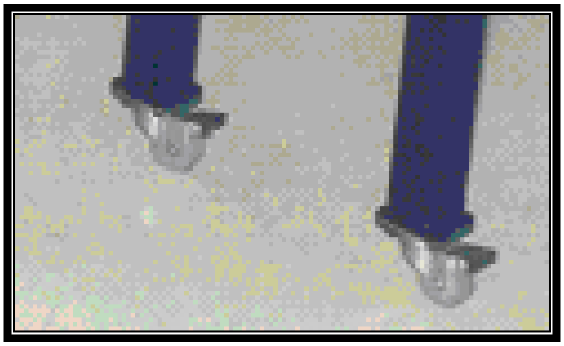


Figure 9.1 Adjustable legs of the Conveyor

The MSS apparatus was designed as a modular technology and therefore exhibited a high degree of flexibility and adaptive capability with respect to the orientation and position of the work piece and pallet within the CIM Cell.

Figure 9.2 Umbilical Cords

The wire connectors to and from the MSS apparatus which were directly, or hardwired, provided an interface between the MSS apparatus and its control hardware was formed by three custom umbilical cables (refer to Figure 9.2) that connected the various feedback sensors and motors to a central control cabinet. The latter umbilical cord connected the PC with the controller; power electronics and sensor circuitry were housed in three circuit compartments fitted in the power electronics box (ref Figure 9.3).

The control and power electronics circuit boxes were fitted with heat dissipating fans to prolong the life span of electronic components that emit heat such as LM12 chip. Quick-release connector units were implemented to facilitate the connection or disconnection of the umbilical cables. The modularity achieved by the implementation of the detachable umbilical cable interface for the MSS apparatus facilitated its repositioning within the CIM cell. The MSS apparatus was designed as a self-contained technology that enabled it to adapt well to changes in its operating environment.

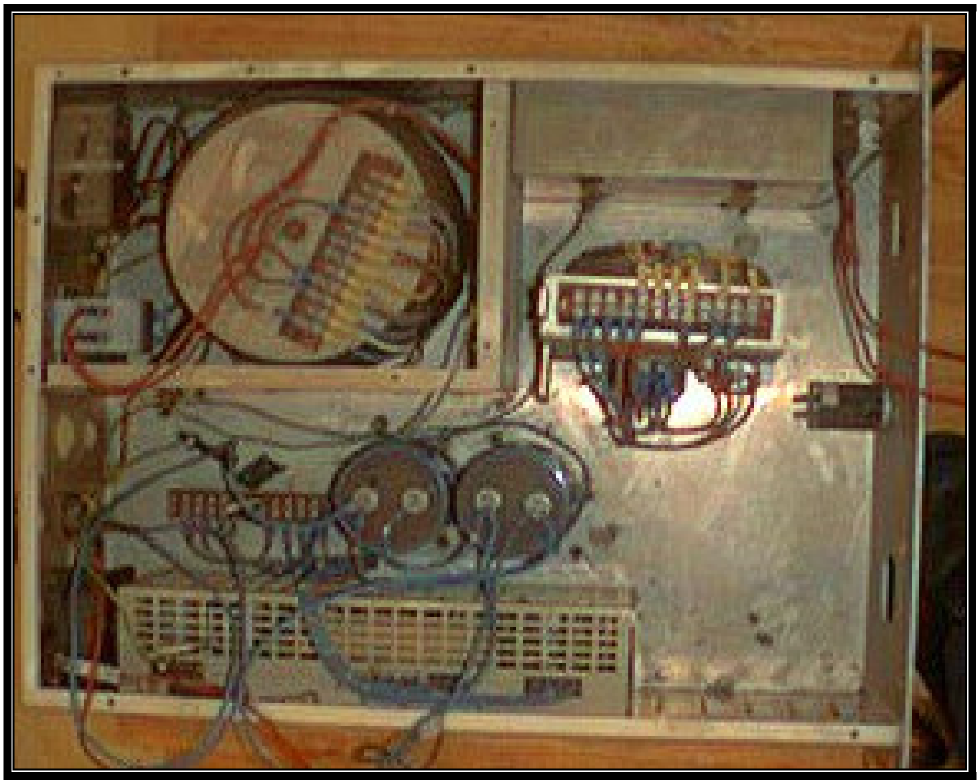


Figure 9.3 Power Electronics Box

9.3 Operational Review of the MSS Apparatus

This section reviews the operational procedures implemented in the MSS apparatus incorporating the transportation of the pallet, its position and movement throughout the conveyor segments. The operational procedure assumed that:

- The MSS apparatus has been successfully implemented in the CIM cell.
- That all the electronic circuitry has been powered accordingly.
- That all the interfacing hardware i.e. PC30GA interface card and associated components has been successfully installed in the PC, and
- That all the connecting cords have been installed accordingly.

The software control programme *frmMainControl*, which was developed using Visual Basic 6, was used to help the operator of the MSS apparatus to navigate to different control programmes controlling different functions of the MSS apparatus. Other software controlling programmes for different mechanisms of the MSS apparatus formed sub- programmes of the main control programme. The software served as a graphical user interface (GUI) between the operator and the MSS apparatus.

The MSS apparatus was designed to be user-orientated. The operator interacts with the MSS apparatus with the GUI, which is used to browse between the different controls programmes of the MSS apparatus. When the MSS control software is run, the user interface [*frmMainControl*] is shown on the screen. The MSS apparatus was modular designed and this resulted in it being modular in operation and control.

9.4 CASE STUDIES ON THE APPLICATION OF THE MSS AND RELATED APPARATUS

This section presents case studies of the operational procedures adopted by industrial systems similar to the MSS apparatus. The aim of these case studies is to enhance the reader's understanding of the overall function of the sensor based control similar in operational to the MSS apparatus and to highlight the re-configurable nature of the system.

9.4.1 Case Study 1: Real Time Tracking and Control in a Manufacturing Plant

Problem

A large domestic manufacturer of TV sets, faced with price erosion from foreign competition, decided to investigate the potential savings available from automating their manufacturing plant. A critical component in the final assembly process is the enclosure, the TV case. An insufficient quantity or an incorrect model number can result in slow down or even a halt of final assembly. A survey of the current operation disclosed a very labour intensive procedure for tracking and controlling the inventory of TV cases coming out of production. Other problems encountered included errors in production counts due to manual data entry, misplaced products in the warehouse, and inaccurate on-hand inventory counts.

Solution

TV cases with the same model number are removed from injection moulding machines and placed in large cardboard containers. A bar code was applied to the side of the container to identify TV case part number. Containers are then transported by conveyor past a fixed-position moving-beam laser scanner (ref Figure 9.15). The code is read and transmitted to an inventory computer, E, which updates a production count. Containers then travel past a second moving-beam laser scanner interfaced to a sortation controller, B. The sortation controller tracks and diverts containers into vacant accumulation lanes. Forklift truck drivers using on-board radio frequency terminals, D, receive instructions from the inventory computer, E, through a base station link. The inventory computer dispatches the driver to either move the material to final assembly, or assigns the warehouse section in which the containers are to be placed.

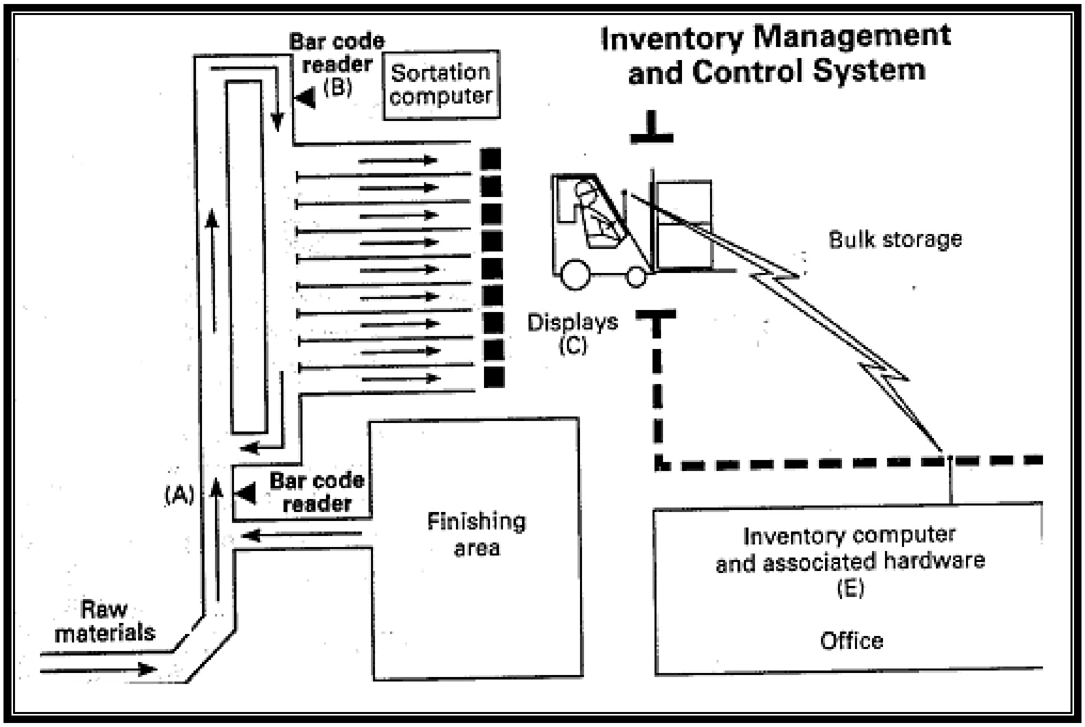


Figure 9.15 Layout diagram for the Case Study

9.4.2 Case Study 2: Vision Based Sensor and Navigation System for Autonomous Eerial Vehicle Refuelling

Unmanned Aerial Vehicles (UAV's) have many important applications ranging from military to research and everyday civilian uses. One of the most difficult technological hurdles to overcome in autonomous in-flight refuelling is the need for a highly accurate sensor to measure the locations of the tanker and the aircraft (ref Figure 9.16). The GPS was used but it had accuracy limitations.

This sensor accuracy problem was overcome by utilizing a revolutionary Vision-based Navigation system called VisNav developed by researchers at the University of Texas A&M (Gunnam). The VisNav is capable of providing the needed six degree-of-freedom information for real-time navigation, and can enable accurate autonomous aerial refuelling without extensive alterations in the current refuelling systems. It can be applied to both the current probe-and-drag as well as the boom method for refuelling. VisNav comprises a new kind of optical sensor combined with structured active light sources (beacons) to achieve a selective or "intelligent" vision. VisNav structures light in the frequency domain, analogous to radar, so that discrimination and target identification is near-trivial even in a noisy ambient environment.

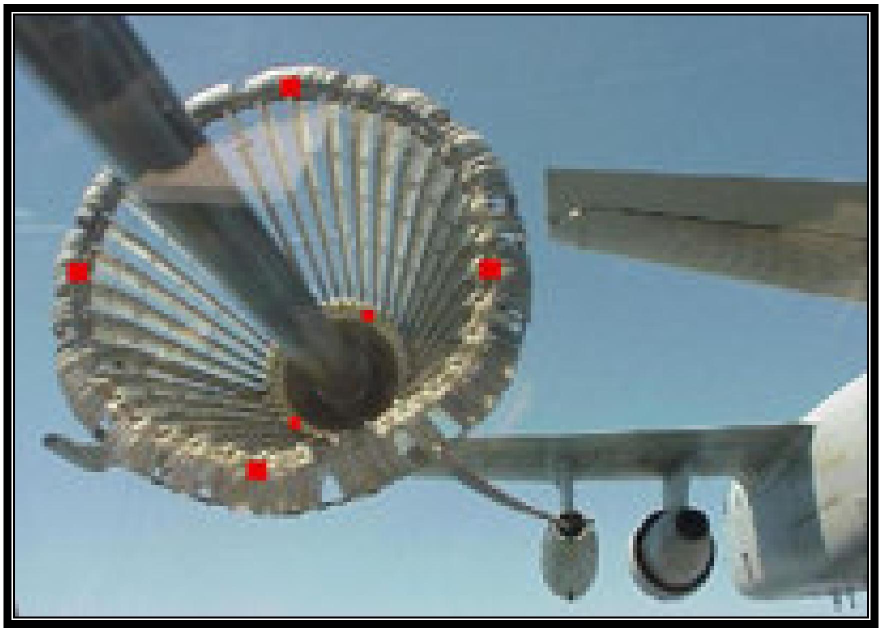


Figure 9.16 Autonomous Arial Vehicle Refuelling

Several Light Emitting Diodes (LED) called beacons, are attached to the refuelling target frame A, and an optical sensor, or Position Sensing Diode (PSD), on the aircraft frame B. The LEDs emit structured light modulated with a known waveform; filtering of the received energy allows all ambient energy to be ignored. Thus VisNAv can be used in 100 percent cloud cover, total darkness, and adverse weather conditions. The position of the light centroid on the PSD is directly related to the centroid of the beacons with respect to the location of the PSD on the aircraft. A Gaussian Least Squares Differential Correction (GLSDC) routine is used to calculate the six-degree of freedom data at an update rate as high as 100 Hz.

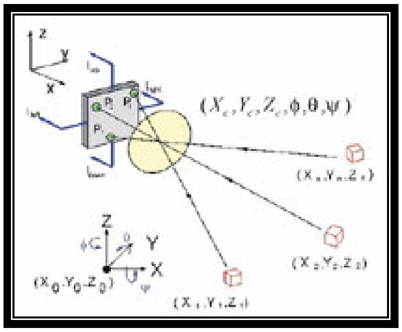


Figure 9.17 VisNav Design and Orientation

9.5 Chapter Summary

This chapter discussed the implementation of the MSS apparatus in the computer integrated manufacturing (CIM) environment and reviewed the characteristics of the apparatus that facilitated its successful integration. The importance of the MSS apparatus to seamlessly integrate with other existing components within the CIM cell was discussed.

Chapter 10

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 Introduction

This chapter summarises the conclusions, major contributions to the body of knowledge by this thesis and it indicates future research and development directions that would help to bring the advantages of the proposed shop floor control system into industrial practice. The primary goal of this thesis was to develop and design a general model utilising mechatronic systems to facilitate tactical and decision making for operation in a CIM environment. This research project further proposed to develop, apply and evaluate the use of MSS apparatus within the operation of a CIM cell, integrated with artificial intelligence technology to realise system synchronisation, real-time data acquisition and signal processing.

In the preceding chapters, the requirements, problems and models for the development of the MSS within a CIM cell was introduced and illustrated. As such, a process plan model includes a set of selected CIM cell equipment and various instructions which are necessary for converting raw materials into a finished product. This thesis details the development of MSS system that could be used to implement automated quality control tasks in flexible manufacturing systems. The MSS was successfully integrated into the research orientated Computer Integrated Manufacturing system at the School of Mechanical Engineering of the University of KwaZulu Natal, Durban (ref Figure 10.1). The MSS has been developed as a flexible, PC-based technology that implements a series of IR emitter and receiver sensors strategically placed along the conveyor and single scanner sensor system. These emitter and receiver pairs enabled the conveyor segment operation as well as tracking and exact positioning the pallet on the conveyor belt. A single scanner sensor was used to automatically capture data from the shop floor utilising machine-readable bar code system (refer to Chapter 5). The MSS apparatus was developed using an original modular design approach, reviewed earlier in this thesis.

10.2 Advances in Mechatronics

Mechatronics, as an engineering discipline, strives to optimally integrate mechanical, electronic and computer systems in order to create high precision products and manufacturing processes. As an interdisciplinary subject it has now evolved to incorporate optical, communication, and information technologies. In particular, optical sensing and data processing technologies are being integrated, at an accelerated rate, into mechatronic systems because these optical based technologies provide components for high precision, rapid information processing, and smart functions. The *enhanced mechatronic technology* can be utilised for a variety of applications that require precision sensors and actuators, optical-based process monitoring, robust control devices, intelligent vision systems, and high-density information storage devices.

As a result of this evolution, products, processes and systems are becoming smarter, more accurate, and more human-friendly than those of the past, and these opto-mechatronic technologies will continue to play a leading role in the development of intelligent products and systems in the coming years.

10.3 Objectives Achieved

The following thesis objectives have been achieved:

- Custom-built emitter-receiver sensor pairs, LDRs were installed at strategic positions along the conveyor segments; custom-designed H-bridge motor drivers (Chapter 4) were installed on the CIM cell and interfaced to the Eagle PC30GA Data Acquisition (DAQ) card. The hardware has remained stable throughout months of testing. This was covered extensively in Chapter 7.

- Microsoft Visual Basic 6 (VB6) software source code was developed to utilise the DAQ card's internal counters to measure pulses from the sensors are received on the digital I/O ports. The software was created to interface with the SFCS using communication protocol, performing the appropriate error corrections when necessary (Appendix E). VB6 software was also developed to simulate and model the behaviour of the CIM cell components. The simulation was seamlessly integrated with the shop floor control system, allowing developers to switch between simulated and real environments by adjusting a single variable. A VB6 Graphical User Interface (GUI) was created so that the pallet movements in the modular conveyor segments can be tracked in real time, both in simulation and in real world. The GUI for the CIM cell was covered in Chapters 7 and 8 respectively.

- The sensor data where the raw signals that are conditioned for use by the localisation algorithms. A technique was developed to apply direction to the raw sensory data. Several sensor filters were investigated for the sensor signals (Chapter 7).

- An algorithm was developed that combined the pallet velocity, real-time pallet position visualisation and bar code scanner information. Various sensor fusion techniques were considered, including Bayesian inference, Dempster-Shafer inference, fuzzy logic and neural networks (Chapter 5).

- Extensive tests and calibration were performed on the test bed in order to measure and refine the MSS's performance. The results of these tests were elaborated in Chapter 8.

The development of shop floor control software requires a formal methodology to reduce the development cost and time and actively cope with dynamic changes occurring in the system. Although a number of approaches to the formal specification and development methodologies on such purposes have been presented, their contexts do not focus on distributed shop floor control. Consequently, they lack

- The specification for a distributed SFCS,
- Automatic generation of contents, and
- Integrity between specification and development methodologies.

To overcome these disadvantages, this thesis proposed a methodology to model a MSS apparatus to generate a distributed SFCS rapidly from formal model-based conveyor control software specification.

10.4 Major Contributions by the Research

The major contribution of this thesis is to provide SFC engineers with a rapid and integrated way to the development of a distributed SFCS.

More detailed contributions were made as follows:

- A formal methodology of modelling, designing and analysing a CIM cell control systems using mechatronic sensory system.

- A fast modular affordable cost plug and play solution to industrial shop floor control systems (SFCS).

- The set of formal models provide engineers with a simple and structured way to the specification in the context of a distributed SFCS.

- The resource relationship model makes the developed SFCS scalable so that a new controller can be easily added without a change in existing controllers.

- The monitoring-execution model facilitates the automatic generation of program codes associated with communication with UCDs and other controllers.

- The control software specification methodology enhances the reuse of existing formal models so that newly added controllers can be easily and rapidly reproduced from the models.

10.5 Recommendations

For the demonstration of the proposed MSS apparatus, a prototype system was designed, implemented and tested at a test bed at the School of Mechanical Engineering, Mechatronics and Robotics Research Group (MR^{2}G), University of KwaZulu-Natal.

The following are recommendations for future research in this area:

(i) Results obtained in this research were under a test bed conditions even though industrial attenuations were considered, it is imperative to bridge the gap between industry and academe. Therefore efforts must be made, in future, to disseminate past, present and future results with potential to the industry in order to evaluate them under real conditions.

(ii) The proposed operation of the MSS apparatus within CIM cell has been validated to a certain extent; however such validation should be realistic taking into account of all industrial based environments.

(iii) For manufacturing, the use of standards is of paramount importance for achieving flexible systems. Therefore, standards and standardisation should be studied to ensure the reference architecture is compliant and make efficient use of standards.

(iv) Although the MSS apparatus showed to be very robust, optimisation of the algorithm is still possible. Presently, the conveyor operational control is based on IR sensors triggering during a half weaving cycle. By extending the measurements to one full cycle, pitch control may be optimised.

(v) New sensors that were employed on the MSS apparatus can be added to the sensor fusion algorithm by assigning the appropriate weights. However, as the number of sensors increases, the weighted average scheme will become less effective. At some point a more complex algorithm such as Bayesian or Dempter-Shafer scheme or neural network may become necessary.

10.6 Chapter Summary

This chapter has summarised the conclusions, major contributions to the body of knowledge by this thesis and it indicates future research and development directions that would help to bring the advantages of the proposed MSS apparatus into industrial practice.

Chapter 11

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