COMMUNICATION, MAPPING AND NAVIGATIONAL ASPECTS FOR A FREE-RANGING, AUTOMATED GUIDED VEHICLE

JAMES ASBURY

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ABSTRACT

A free-ranging automated guided vehicle incorporating navigation and radio communication for use in a fully automated flexible manufacturing system has been developed. A vehicle, operating as a complete subsystem, was built and tested in an integrated control environment and proved to have promising results.

Various radio communication techniques are examined and the design and testing of a low cost, wireless, two way communication link is detailed. A novel, flexible infrared navigation technique was developed and incorporated into the AGV subsystem. Path planning and a flexible real time path modification system was formulated using an innovative program with an interpolative visual display unit and digitiser. Data transfer to and from the vehicles in a real time integrated system is covered. System integration for an free-ranging automatic guided vehicle is discussed covering aspects of communication, mapping and navigation.

Specific needs for a free-ranging automatic guided vehicle, are presented. The unique design features of navigation and mapping outlined in this thesis has resulted in a low cost, free-ranging, autonomous automatic guided vehicle.

This thesis is dedicated to my father, John Robert Asbury, and my mother, June Jennifer Asbury, for their untold patience and support.

PREFACE

The research work presented in this thesis was performed at the Mechanical Engineering Department at the University of Natal, Durban, under the supervision of Professor Z. Katz.

The work performed is as a direct result of James Asbury's own work, and has not been submitted in part, or in whole, to any other University.

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LIST OF ABBREVIATIONS

4DPSK - Four Differential Shift Keying

ASCII - American Standard Code for Information Interchange

AGV - Automatic Guided Vehicle

A.L.F. - Automatic Line Followers

CAP - Central AGV Processor

CMOS - Complementary Metal Oxide Semi-Conductor

C.I.M.S. - Computer Integrated Manufacturing Systems

CNC - Computer Numerical Control

DCE - Data Communication Equipment

DOS - Disk Operating System

DTE - Data Terminal Equipment

EBCDIC - Extended Binary Coded Decimal Interchange Code

EPROM - Erasable Programmable Read Only Memory

ETA - Electronic Industry Association

FM - Frequency Modulation

FMS - Flexible Manufacturing Systems

FSK - Frequency Shift Keying

GMSK - Gaussian Minimum Shift Keying

GPS - Global Positioning System

GSK - Gaussian Shift Keying

I.S.O./O.S.I - International Standards Organisation Open Systems Interconnection

M.A.P. - Manufacturing Automation Protocol

MOSFET - Metal Oxide Semi-Conductor Field Effect Transistor

P.L.C. - Program Logic Controller

PCM - Pulsed Code Modulation

PSK - Phase Shift Keying

PWM - Pulsed Width Modulation

QAM - Quadratic Amplitude Modulation

RAM - Random Access Memory

RIA - Robotic Industries Association

ROM - Read Only Memory

RTS - Request To Send

T.T.L. - Transistor Transistor Logic

VHF - Very-High Frequency

UHF - Ultra-High Frequency

CHAPTER ONE
INTRODUCTION

1.1 Historical Background to AGV Systems

The technology that spearheaded the birth of AGVs can be traced back to the original conceptualisation of robotics. It is therefore considered appropriate to present a historical synopsis of robotics before examining the evolution of AGV systems. The word robot was coined in the 1920's by playwright Karel Capek from the Czechoslovakian word 'robota', appropriately meaning work. The science fiction writer Isaac Asimov invented the word 'robotics' referring to the science of robots. Asimov wrote a series of novels in which he imagined a world of mechanical beings who were humanity's devoted helpmates. His concept seems accurate when one considers the variety of tasks robots perform. These range from shearing sheep in Australia, moulding rice cakes for sushi in Japan, transporting commuters via robotic trains in European cities, executing surgical procedures in hospitals, to navigational 'smart weapons'. Robots are suited to many environments, often ones unsafe for human beings, whether it be out in space such as the space probe Voyager I, at the bottom of an ocean or in a nuclear fall out zone. Robotic machines function without benefit of oxygen and can withstand extreme temperatures and pressures. They are also capable of working lengthy periods of time without supervision. Lacking the human quality of emotion enables robots to perform those tasks considered too tedious, precise or dangerous for people.

Scientists and engineers have fervently debated the definition of 'robot', failing to reach a consensus. The Robotic Industries Association (RIA) was founded in 1974 as the Robot Institute of America. It consisted mostly of manufacturers and users of industrial robots. Members of the RIA argued at length before issuing a rather wordy concessionary definition in 1979 (Gibbons, 1987). The definition submitted defined the word robot as 'a reprogrammable multi-functional manipulator, designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks' (Gibbons, 1987). This was later modified to include machines equipped with vision and other sensory systems (Gibbons, 1987). However, the development of intelligent autonomous vehicles such as the 'Voyager 2 space probe', and machines with skills other than manipulation, implies that this definition is not broad enough.

As late as the 1940's, AGV's per se, had not materialised. In the broader sense, terms such as 'mechanical men' and 'thinking machines' began to appear. Machines evolved from performing purely physical functions to ones where they began to replace human intellect. A crude servomechanism was envisaged by David B. Parkinson of Bell Telephone Laboratories and later implemented by Western Electric Company in the M-9 anti-aircraft gun (Gibbons, 1987). The unique aspect of this control instrument lay in the fact that it was one of the first to not only replace a human operator, but, furthermore could perform the task more rapidly and far more precisely.

The first pioneer AGV systems were developed in the 1950's by Barrett Electronics Corp (Grand Rapids, MI) (Hammond, 1986). They were termed 'driverless systems'. Three companies, namely, Barrett, Jervis B. Webb, and Clark, competed over the years with the rudimentary AGV systems known as 'tuggers'. These were simple driverless vehicles that followed fixed guidepaths and used to drag or tug 'trains' of goods. However, they received poor acceptance in the USA, especially from the industrial work-force. The unions saw them as a direct threat, often resorting to sabotage of AGV systems. In addition, the vendors tended to offer only standard product lines, and were reluctant to customise vehicles or controllers to meet customer's specific needs (Hammond, 1986).

Even though AGV systems originated in the United States this technology caught on much faster in Europe. In this same decade (50's) the United Kingdom followed suit with their version of an AGV system. It was called a Robotug. These guided vehicles were then known as Automatic Line Followers (Corran, 1986). Progress in the development of AGV systems in Europe was due largely to the fact that European workers were not as intimidated as their American counterparts. European companies had a certain degree of job protection, while stricter regulations with regard to safety and the work-place environment, often necessitated automation, regardless of the cost.

The inherent nature of AGV's made them totally dependent on the state of the art electronics of the time for their development. Originally AGV systems were designed for simple material handling in warehousing environments. These were based on elementary techniques of wire guidance similar to those presently in use. They were stand alone vehicles of the tugger or 'driverless tractor' type, and were used to pull a series of trailers. These vehicles executed simple, rudimentary tasks, usually saving on operating costs. They were also utilised in environments incompatible to humans. These were cumbersome and complicated in structure, implementing relay logic in their control circuitry. There was no central computer or onboard micro controller to facilitate in guidance and communication. All communication was confined to zone or cell controllers (Corran, 1986). The primary function of the cell or zone controller was to prevent collisions by providing a basic safety function. Other functions instituted were the rudimentary control of routing, in the form of track switching and the control of stops. This halting function enabled the AGV system to facilitate communication with the zone controller usually implementing some form of tactile interface (Corran, 1986). The control system was based on vacuum tube technology and was both bulky and relatively inflexible.

Two main guidance technologies evolved, and these are still the most widely used today: inductive wire guidance, and optical guidance. Considering that these vehicles were to function in an already human environment, as stand alone units, collision avoidance and safety precautions were prioritised alongside guidance technology. Zone theory became the most favoured technique of vehicle management. This concept divided an AGV mapping area into separate zones or blocks. Each block allowed for only a single vehicle to occupy it at any one time. Various technologies were implemented to control and communicate with vehicles allowing them to enter or leave zones. Light, sound or electromagnetic signals were used for communication. Relay logic circuitry and its complicated interconnection between zones was usually not cost effective and only implemented in unusual circumstances or in custom designed plants. Although in later years the concepts of wire and light guidance technology persisted, relay logic, bulky inefficient motion control and the rudimentary communication systems, were to be replaced (Corran, 1986).

In the late 1950's, transistor technology replaced the vacuum tubes, making the controller systems less bulky, more reliable and at the same time increasing their capabilities. However, in most cases even transistor technology was still too expensive for complex manufacturing material handling problems experienced in industry.

A significant advancement of the 1960's was the development of simpler electronic logic. This reduced the complexity of circuitry and hence installation and maintenance costs. Primitive solid state electronic devices became available consisting of diode-transistor logic and this replaced much of the earlier relay logic of the 1950's.

It was not until the early 1970's that significant advancement in electronics technology occurred. Integrated circuitry using discrete transistors interconnected on a silicone substrate became commercially available at a low cost. These advancements allowed for far simpler logic and motion control, while achieving better efficiency and lower cost. Ironically, it was these early developments that now enable the manufacturing of comparatively low cost integrated circuits through the use of AGVs and robotics in their production.

As already stated the sophistication of AGV vehicles and systems has been directly related to advances made in the electronic industry. Initially, progress occurred mainly in the fields of solid state technology, computer technology, integrated circuit technology, optoelectronics and telecommunications resulting ultimately in the microprocessor. The advances in micro-processor technology and its associated high and low level programming languages has had the greatest impact on the development of AGVs (Corran, 1986).

Another breakthrough in solid state electronics was the introduction of thyristors and triacs. These devices were used for a.c. power control. Later, Tröge Choppers and similar technology developed. These technologies implemented triacs and thyristors and this resulted in high efficiency d.c. power control. This technology, although popular in the late 1970's, required complex design and complicated control circuitry to ensure reliable d.c. power management. One of the latest developments in electronics to influence AGV power management has been the progress made in power Metal Oxide Semiconductor Field Effect Transistor (Mosfet) technology. This has revolutionized d.c. power control rendering it simple, low cost and efficient (Freeman, 1979).

These advancements in electronics allowed for the first introduction of versatility in automation and control. This was achieved through the development of a program logic controller (P.L.C.). These were the first programmable control devices commercially available. Flexibility opened up new perceptions for AGVs. The concepts of free-ranging AGVs with regard to flexible manufacturing systems arose. These vehicles were considered to be ones which could follow imaginary guidepaths implementing some form of positional guidance. The perception of autonomous vehicles later followed. These included vehicles that determined their specific paths by considering a predetermined instruction set as well as factors in their immediate surroundings. This conceptualization was boosted even further by the introduction of compact, low cost micro-computers. This vision still required much progress in the field of communication, navigation and efficient, low cost power management.

A further breakthrough occurred when microcontrollers were utilized on-board AGVs, thus producing 'smart' vehicles. These microcontrollers allowed vehicles to determine their own routes to designated destinations. Furthermore it facilitated a higher level of communication, and permitted the control of functions such as palette loading and unloading. Likewise, the system controller became much more complex, to the point that it was able to interface with systems such as conveyors, robots, Computer Numerical Control (CNC) machines and a multitude of other automation devices (Koren, 1983), (Madwed, 1984). Remote location devices could request material delivery. Vehicles could then be dispatched via the system controller which would supply it with the information necessary to manage its load and route. Material could be tracked throughout the facility, giving a much improved method of inventory control (Koff & Boldrin, 1985).

In the 1980's, industry in the United States re-evaluated its position on automation, and began to devote more research to advanced automation programs. This was further enhanced as vehicle and system developments made in Europe were transferred to the United States through a series of licenses and ventures by European companies. Foreign competition intensified and the recession of the late 1970's and early 1980's was particularly damaging to the American automobile industry. These events forced American industries to look for more efficient manufacturing and assembly techniques. In view of these changes the unions became more receptive to the concept of automation.

Additional development was seen when computer interconnect standards were defined. One of the most popular being the Electronic Industry Association (E.I.A.) RS-232 standard for serial interconnection. This standard defined certain requirements in terms of protocol and hardware between computers. Although this interconnection became very popular, shortfalls such as speed of data transmission, length of transmission cable and number of wires per connection existed. For these reasons other standards have been introduced such as RS-422 and RS-485. Because of the effect of these communications interconnect-standards, free-ranging AGVs became more flexible. Low cost micro-computers became available and a standard for continuous duplex communication was defined. Radio frequency (RF) wireless communication became the obvious next step. Many techniques were suggested for implementing this wireless data transfer, the most favoured being Frequency Shift Keying (FSK). In the mid 1980's discrete integrated circuitry could be purchased to implement this data transfer technique. This promoted the possibility of flexible low cost free-ranging AGV implementation further. The diversity of components making up a Flexible Manufacturing System (FMS) led to a need for the establishment of a common communications protocol for manufacturing. A standard Manufacturing Automation Protocol

(M.A.P.) was defined and this allowed for a diverse array of intelligent devices within a manufacturing environment to communicate with one another (Main, 1989).

So far no single standard navigation technique for free-ranging AGVs within a manufacturing environment is preferred (Boegli, 1985). It is felt that a specific form of navigation will probably develop that is most favoured for FMS integration. The advancement, by the late 1980's and early 1990's, in ultrasonic and infrared transducer technology has probably established the basis for FMS navigation of the future. Alongside these developments and the implementation of the standards set out for continuous duplex communication and efficient power management, true autonomy in a fully integrated manufacturing environment is envisaged.

Having reviewed the historical development of AGVs in terms of technological advancements within the Electronic Engineering field, it is now possible to arrive at a working definition of an AGV system.

An AGV system is: 'an advanced material-handling or conveying system that involves a driverless vehicle which follows a guidepath and is controlled by a computer or microprocessor' (Hammond, 1986). An AGV is: 'a vehicle equipped with guidance equipment, such as electro-magnetic, optical or imaginary route definition' (Hammond, 1986). The guidance equipment utilises these guide paths to manoeuvre the vehicle to its desired destination. Some form of priority definition usually enables these vehicles to select a predefined route. Utilising an off-board controller, the vehicle is able to receive dispatch commands. The central AGV controller, in turn, receives information of the vehicle status, position within its environment, and confirmation of tasks (Shull, 1986). Since they are driverless, guided by imaginary paths or paths on or in the floor, these vehicles can effectively be interfaced with material handling subsystems or workcells (Miller, 1987).

From this working definition of AGV systems a manufacturing AGV can be categorised into the following functions: It must have the ability to move from one location to another either utilizing on board power or some external power source. It must have the ability to follow a predetermined guidepath. This path should be optimized for the material flow pattern of a given application. For free-ranging AGVs, navigation and navigational guidance techniques are usually a prerequisite. Free-ranging AGVs must have the ability to communicate with a central AGV processor. Data needs to be transferred through some form of wireless communication link. The central AGV processor must have the capability to co-ordinate and decide on vehicle trafficking and have some interface either with an operator or other subsystems.

To integrate a materials handling system into a flexible manufacturing environment, a predefined communication protocol is necessary. The most notable set of protocols applicable to the field of AGV operation in a manufacturing environment is the Manufacturing Automation Protocol (M.A.P.). This may be used to integrate elements of a manufacturing cell supplied by different vendors. This could include integration of different elements, such as robotic welders and computerized machinery. These systems can also be integrated with a materials handling control processor forming 'islands of automation' controlled by a production engineering control centre. The M.A.P. could interface this manufacturing cell with a control production computer which would supervise the entire FMS (Fiorletta, Lennard & Harper, 1987), (Gould, 1990).

The transmission medium for M.A.P. is defined as a broadband data transfer, spanning up to 10 million bits per second. Using the M.A.P. structure, large amounts of data may be transferred rapidly throughout the working environment. However, in a materials handling system, large amounts of instruction information between the production mainframe and the CAP is not necessary for efficient operation. By correct utilization of the CAP, vehicle routes may be scheduled or re-scheduled as well as path structures redefined to suit dynamic requirements. Simulators for analyzing, planning and designing AGV based material handling systems, have been developed. These are usually designed to suit specific FMS requirements. Specialized control centres are instituted to simulate separate 'islands of automation'. Each of these work cells is then linked to a common central controller. 'Islands of automation' have integrated facilities such as computerized machinery, robotic welding and an integrated materials handling system (McElroy, Stephens, Bonnell & Gorman, 1989). AGVs with fixed guide paths and little or no intelligence impeded the development of a flexible materials handling system. The introduction of intelligent free-ranging AGVs has made flexibility in FMS environments possible. Although this diversity has opened up new concepts in dynamic materials handling, challenging obstacles involving control, as well as vehicle management problems, have arisen. Each control environment and management approach determines the operating effectiveness of the transportation network and ultimately the FMS (Lui, 1989), (Lim, Siong & Choon, 1989).

Hardware failures within an automated environment can cause complete system failure if a systematic design involving simulation strategies is not adopted. Free-ranging AGVs with dynamic path rescheduling are required for integration into these simulation strategies (Gaskins & Tanchaco, 1989), (MacLeod & Lun, 1992). The potential of free-ranging vehicles with flexible path rescheduling and possible real time path restructuring have unlimited possibilities. Promising advantages can be gained such as congestion avoidance and materials handling optimization. Smart vehicle utilization can reduce the number of vehicles required which, in turn, will reduce the complexity of simulation and congestion, ultimately reducing capital and running costs (Gaskins et al., 1989), (Ben-Arieh, 1991).

Computer integration for production and management control is becoming increasingly popular within FMS. This is known as computer integrated manufacturing system (C.I.M.S.). System management includes the structuring of all possible alternatives for each vehicle and machine situation within islands of automation (Hammond, 1986). Interaction between the production mainframe controller and CAP is of great importance in defining high efficiency transportation routes at minimal cost (Gaskins et al., 1989).

In accordance with the RIA's latest definition, an AGV is not a robot in the full context, but rather 'an intelligent or semi-intelligent unit which performs tasks by moving from one place to another under a certain set of conditions' (Miller, 1987). The essential capability of an AGV is its ability to move from one location to another following a predefined path under computer control. This is a unique capability in the automated factory. Robots cannot provide the mobility of the automated guided vehicle system, and conveyors do not offer the flexibility (Miller, 1987). AGV systems and industrial robots not only utilize similar advanced technology and focus on increasing industrial productivity but they can also work together in some applications. Two possibilities are interfacing AGV systems and industrial robots to provide automatic loading and unloading functions and mounting an industrial robot on an AGV system to achieve mobility. It is from this latter possibility that the term mobile robot is derived (Miller, 1987).

The advancement of free-ranging AGVs within the manufacturing environment is a relatively unexplored area of technology. Based on the current available literature, there is still not a preferred communication, guidance or navigation structure for the integration of free-ranging AGVs into the manufacturing environment. It is felt, however, that duplex communication using a wireless radio link between the AGV and CAP will probably be the most viable. Various complicated guidance algorithms have been derived to enable efficient AGV movement. Nevertheless, it was believed that a relatively simple guidance technique would suffice for the application. The implementation of this concept in this research application verified that a simple guidance algorithm is acceptable in most situations. At present, there is no preferred navigation technique for free-ranging AGV's within a manufacturing environment (Boegli, 1985). This is due to the fact that various advantages and disadvantages are associated with each procedure such as interference, ease of installation, cost of installation, ease of implementation and accuracy.

1.2 Motivation

A primary motivation for this research lay in the potential it holds to contribute towards the knowledge for the advancement of free-ranging AGV systems. Free-ranging AGVs should be developed for application within the South African environment in keeping with world wide trends. Based on the research and development gained herein, the basic groundwork for free-ranging AGVs within the South African manufacturing environment can begin to be theorised. To keep abreast with technical progress, the South African manufacturing sector has experienced a trend towards automated manufacturing. These developments have been sensitive to the large labour market and therefore have maintained a high operator interface. The need for free-ranging AGVs lies within heavy industrial materials handling, as this is an area that is unsuitable and hazardous for manual labour.

The main objective of this research is to develop an accurate navigation system which is easily implementable, modifiable and expandable. This system should be insensitive to interference allowing for a wider application while still maintaining a relatively low cost. The use of the infrared spectral medium and correct design procedures should result in minimal interference. Furthermore, development in technology continues to lower the costs of infrared transmitter and receiver component circuitry. Rapid developments in this technology have increasingly popularized its implementation in many consumer applications.

This thesis proposes the development of a free-ranging vehicle. It details an accurate, novel, flexible infrared navigation technique. Radio communication methods are examined and a duplex modem design presented. Path planning and a flexible real time path modification system is specified employing an innovative real time vehicle management system.

1.3 Overview

In order to facilitate easy reading an overview of the organisation of the chapters is provided.

Following this introductory text, the second chapter details the various wireless communication methods investigated. From this literature survey a design is formulated. Details of this design which entails a frequency modulated wireless radio link incorporating a simple frequency shift key (FSK) modem is offered. The design procedures for the modem are detailed in Appendix I.

A literature survey on various guidance techniques is then presented. A program is detailed which enables an operator to structure an AGV working environment from a central AGV processor. An explanation is given of the guidance philosophy incorporated in the CAP program. Furthermore, an account of the associated guidance technique developed for implementation onboard the AGV is presented.

In chapter four an infrared navigation system with fixed transmitter beacons termed System I is discussed.

System II, the focus of this research, is described in chapter five. This is an alternative infrared navigation system with fixed receiver beacons.

System III, a proposed infrared system, is suggested in chapter six. Additionally, a detailed discussion of the results on communication, guidance and navigation is provided.

For a clearer understanding of the experimental hardware apparatus used in this research application the specifics of the vehicle layout are presented in Appendix I. Appendix II details theoretical calculations. Appendix III provides relevant additional literature.

CHAPTER TWO
COMMUNICATIONS

2.1 Introduction

In order to address the concept of communication in AGVs it is necessary to review the growth of wireless communication, as well as the various forms of wireless communication employed. From this basis a detailed discussion of radio frequency as a medium for wireless communication and its associated data transfer techniques, as well as common protocols used for data integrity checking is furnished. This then lays the foundation for the choice of Frequency Modulation (FM) radio as a medium, and for FSK as a data transfer technique. A combination of standard protocol checking employing checksumming techniques is presented.

As AGV systems became more complex, sophisticated methods of communication evolved. The need for flexibility necessitated the development of AGVs from non-free-ranging to free-ranging in the working environment. For this to be achieved AGVs had to depart from non-flexible guide paths to flexible imaginary guide paths that could be altered easily to suit the needs of the changing working environment. The nature of this dynamic path structuring demanded some form of wireless communication between a central controlling computer and an AGV.

Initially the main advantage of wireless guidance was that AGVs systems then possessed the ability to change guide paths easily. This allowed for the concepts of a fully automated manufacturing environment to become plausible. The introduction of fully automated flexible manufacturing systems resulted in a more dynamic approach to free-ranging AGVs. Two-way wireless communication and flexible path planning meant that an AGV's path structure could be dynamically rescheduled to satisfy the new needs for flexibility currently required within the manufacturing environment. This enticing prospect has opened up the way for broader concepts of free-ranging vehicles to be introduced.

Initially, communication requirements for the original AGVs were in the form of rudimentary instructions, usually given by an operator programming a set of switches on the AGV's control console (Corran, 1986). This programming instructed the vehicle to stop at certain floor sensors or select a particular route at a given junction. Floor sensors consisted of reflective white tape making up a primitive bar code, each code defining a particular instruction. Magnet arrays were later introduced replacing bar codes and resulting in clearer programming instructions. This proved to be successful as they had the advantage of being able to work in dirtier environments. As technology progressed, switchable inductive loops were used, passing primitive electromagnetic signals to the AGVs at selected stations. Without intelligent onboard controllers, communication was usually simplex in nature. Instructions were directed from the Central AGV Processor (CAP) to the AGVs without confirmation. This problem often lead to misinformation and vehicles becoming 'lost' or misinformed.

It was not until the seventies that microprocessor AGV intelligence appeared. This had a profound impact on AGV development as error free, duplex communication could now be achieved. The CAP instructed vehicles to perform certain functions rather than issuing specific step by step instructions and the AGV could return intelligent meaningful data to the CAP. This data could then be utilised in 'islands of automation'. Intelligent vehicles were preprogrammed to interpret instruction sets issued by the CAP. These instructions could be interpreted on board the vehicles and then would simply return confirmation of the work performed.

The advancement in two-way communication and data storage initiated a new kind of AGV in the workplace. Vehicles now had predefined docking stations where intelligent two-way communication ensued. This data transfer was achieved using photo-electric or infrared arrays, later to be replaced with inductive-loops embedded in the floor. Transmitter and receiver loops were placed either side of the guide-path. The AGV was equipped with transmitters and receivers directly above these embedded loops. Herein lay the beginning of continuous, duplex, wireless communication. Frequency Shift Keying (FSK) was the most popular data transfer technique and this method is still the most favoured in present day AGV wireless data transfer. Inductive-loops had high capital costs because of the extensive wiring needed and this prompted the development of inductive communication using the inductive guide wire. This was achieved by superimposing higher frequencies on the inductive guide-wire carrier frequency and then decoding and filtering the received signal (Premi & Besant, 1983).

If AGVs are to be truly free-ranging, then communication has to be wireless in its nature. In all wireless communication, interference must be considered and the integrity of the data should always be verified. Wireless communication can be divided into three areas. The first is the medium of data transfer which can be defined as the means for transferring the data from one point to another without the use of wires. The second area, that is, data transfer techniques, can be specific to certain mediums while others can be used on a variety of mediums. The reason for using data transfer techniques is to eliminate the problems of errors due to interference on the medium. The third area is to establish a protocol to determine the logical method of data transfer which can then be used to verify its integrity. The following section embodies a discussion on firstly, the mediums for transporting wireless data, secondly, the transfer techniques utilised and finally, the establishing of protocol.

2.2 Common Mediums used for Data Transportation

Two-way communication via an inductive loop (or the guidance wire) is still the most popular communication method for AGVs. Other mediums used for data transfer are infrared, ultrasonic, radio frequency, visual light, audible sound or a combination of these. Most of the fore-mentioned mediums have the disadvantage of requiring direct line of sight or near line of sight for communication. These above mentioned mediums do not have the ability to negotiate around corners or obstacles. The data carried on these mediums can be lost if the receiver and transmitter are obstructed by an obstacle. Radio frequency overcomes this disadvantage with ease. However, it has the drawback of interference with sophisticated electronics such as microprocessors. This is due to the fact that the motherboards interconnecting copper tracks act as antennae. If these lines have high impedance inputs, a voltage can be induced on them and consequently interfere with the normal functioning of the microprocessor. Similarly, some of the motherboard tracks with their high frequency signals can act as transmitters which will induce electro magnetic waves causing interference with the radio link. For these reasons safety precautions should be investigated, such as installing the motherboard in a Faraday Cage. Radio frequency communication also has the positive benefit of continuous, half duplex or full duplex communication between CAP and AGV. Giordano (1983) utilized an FM radio link between AGV and CAP. Status instructions included battery charge level, loading/unloading, emergency conditions and hours utilized. Research done at Imperial College argues that a dual communication system incorporating an FM radio link as well as infrared transmission has some advantages. They claim that long range omni-directional communication is used for low data transfer rates while infrared direct line of sight communication is used for high transfer rates during vehicle docking (Sen, Wang, Ristic & Besant, 1991). A commercially available example of this is offered on the Tele-Carrier II AGV's designed by Interlake Conco-Tellus (Burr Ridge, Illinois), (Miller, 1987). Another data transfer technique commercially available is infrared communication offered by Allan Translift (Saginaw, Michigan), (Miller, 1987). GEC Electrical Projects offer a commercially available FM radio link which they claim can transmit complete routes to selected vehicles from the CAP controller (Evans, 1988). A further application implementing a wireless communication link utilising infrared is demonstrated by Chin (1989) as well as at the University of Connecticut. Here an array of emitters is used to fulfil the communication process over most of the AGV working area (Olgac & Wood, 1987).

2.3 Data Transfer Techniques

2.3.1 Common Methods of Unintelligent Data Transfer Techniques

The ensuing account of unintelligent communication involving pulse code modulation and pulse width modulation is presented for the following reasons. It is necessary to explain the form of communication that existed between intelligent controller and unintelligent AGVs as this lays the foundation for intelligent two way duplex communication. The original AGVs were unintelligent fixed guide path vehicles with no communication ability. Therefore, micro switches was one method employed to stop or start a vehicle or inform it to take a different guide path. The progression of AGVs to semi-intelligent vehicles, with possibly a semi-dynamic path structure, used rudimentary wireless communication signals as a mechanism of instruction. The mechanism now employed was a wireless switch allowing for partial flexibility of the AGV. Present day state of the art AGV systems incorporate fully intelligent free-ranging vehicles with duplex communication allowing for intelligent instruction sets to be passed between the CAP and AGVs. This allows for free-ranging AGVs where flexible guide paths can be downloaded to the AGV.

It is necessary to detail pulsed code modulation and pulsed width modulation as they can be used for simple unintelligent AGV communications.

2.3.2 Pulsed Code Modulation (PCM)

Pulsed code modulation transfers data as a specific pulse train. Each train of pulses usually indicates a specific instruction or sub-instruction. This pulsed train is decoded at the receiver station and can be associated with a specific set of instructions. This technique is commonly used to transmit a switching command to a specific station. The code is usually sent more than once and this eliminates problems of sporadic errors. There are many commercially available chip sets to encode and decode an instruction; usually a single decoder chip is required for each instruction which outputs a signal when supplied with a specific pulse train. Due to the nature of this transmitting and receiving, it is not commonly used in microprocessor communication where an American Standard Code for Information Interchange (Ascii) character set, with associated binary output values, has been designed for this purpose. This ASCII format can be thought of as a predefined pulse code modulation set (Leibson, 1989). This character set is presented in more detail in section 2.4.

A diagram displaying PCM transfer techniques, is presented below. Here a predefined code is transmitted which is identifiable at the receiver station and translated into a specific instruction. A code data transfer application has been realized in a materials handling environment where specific stations within the environment inform the AGVs of their specific requirements (Dutton, 1990).

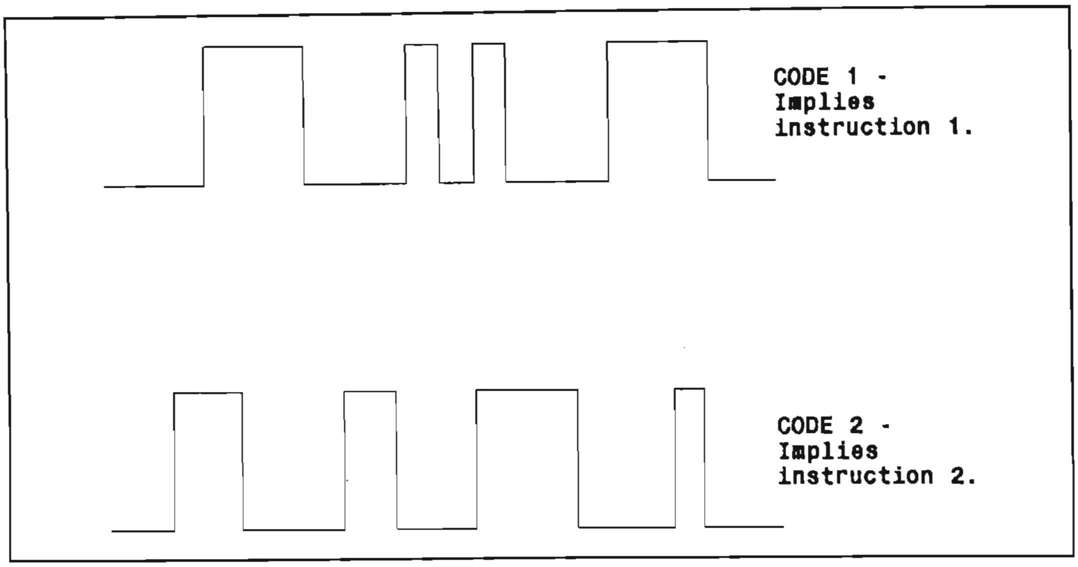


Figure 2-1: Example of PCM Signal Encoding and Signal Decoding

2.3.3 Pulsed Width Modulation (PWM)

Pulsed width modulation is commonly used for analog data transfer. The magnitude of the analog signal is measured by the mark-space-ratio of the digitized high signal to the digitized low signal. This means that if the received signal is proportionally longer in its high state than when it is in its low state, the resultant analog value will be relatively high. When the received signal is proportionally longer in its low state the resultant analog value will be relatively lower. This method combined with FSK is used on modern radio controlled models, to transfer the analog values from the transmitter to the model. The resultant analog value is then converted into a proportional rotation of a servo-motor. When dealing with analog data transfer, sporadic errors due to interference, are not of great concern and can easily be filtered out. However, sporadic errors when communicating between two microprocessors will result in meaningless communication. A diagram indicating this technique of pulsed width modulation is given below.

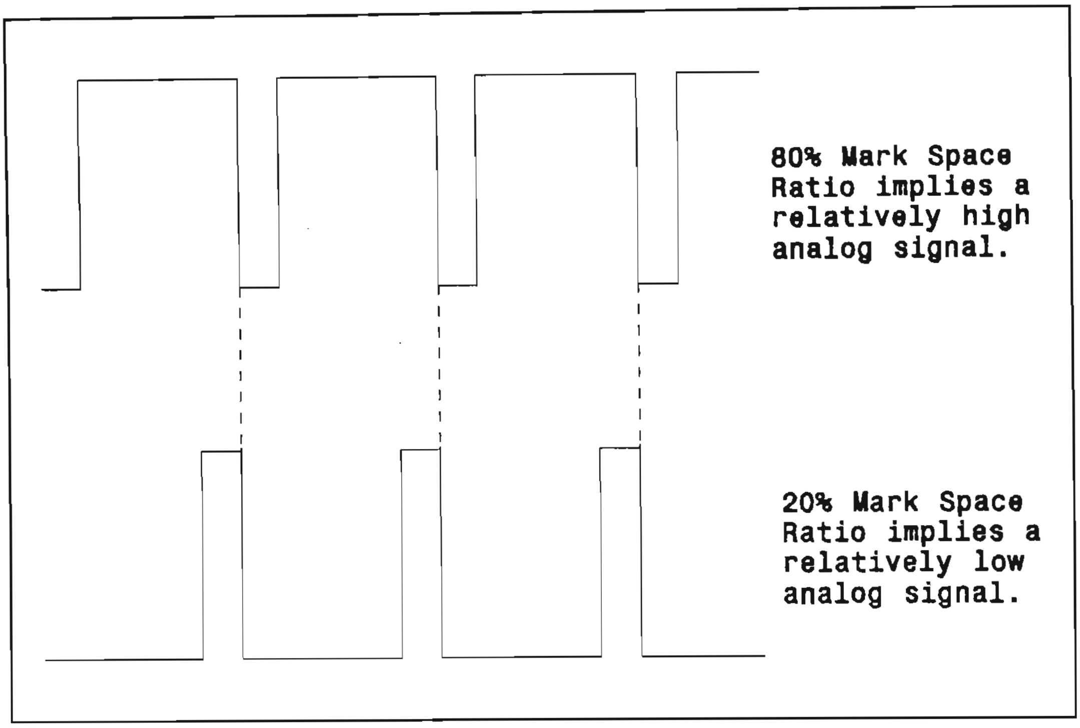


Figure 2-2: Example of PWM Analog Signal Transfer

2.3.4 Common Methods of Intelligent Data Transfer

When communicating between two microprocessors, unidentifiable characters are transferred between the two and these are later deciphered into a meaningful command through the intelligence of the microprocessor.

Most commercially available wireless links are designed for transmitting and receiving speech and, consequently, all the circuitry is designed to operate with a bandwidth of 3 kHz. Any signals with a frequency of less than 300 Hz or greater than 3300 Hz will not pass through the system. This means that if RS-232C was input into a standard wireless communication link then steady state voltages, either positive or negative would not get through and the data stream would be lost.

To overcome this, data transfer techniques have been developed to convert binary data into a form which is compatible with this 3 kHz speech bandwidth. The data is modulated into an audio carrier signal.

The electronic equipment used to convert the binary data into an audio signal is called modulation. Conversion of the audio signals back into the binary data is called demodulation. Normally two way communication is required and, therefore, a modulator and demodulator are required at each station. The piece of equipment that combines these two functions into a single box is called a modem. There are three basic modulation methods: amplitude modulation, frequency modulation and phase modulation. When using amplitude modulation, a frequency in the centre of the passband (eg, 1500 Hz) would be chosen and this would be transmitted at different amplitudes for a binary 0 and a binary 1. This is clearly problematic from the outset where a varying signal strength would result in erratic readings. This method is seldom considered for transferring data over a wireless communication link.

Neither frequency nor phase modulation suffer from the above mentioned drawbacks and are both extensively used for wireless data transfer.

In phase modulation (Phase Shift Keying - PSK) two phases can be used for the high and low states. Detection of phase changes is problematic and a method known as Differential Phase Shift Keying has become more favoured. In this technique, there is a phase shift at the start of every time interval and this reduces some detection problems.

Frequency modulation using a method called Frequency Shift Keying (FSK) is the most common method of wireless radio communication (Exar, 1978). This is covered in detail in the following section.

There are many combinations and variations of the above methods used today with the main objective being to achieve higher baud rates while still satisfying the audio speech bandwidth. Some examples of these are Gaussian Shift Keying (GSK), Gaussian Minimum Shift Keying (GMSK), Four Differential Shift Keying (4DPSK) and Quadrature Amplitude Modulation (QAM).

Most of these methods employ sophisticated electronics to achieve higher baud rates. A complex modem design for achieving improved bit transfer rates sacrifices performance because of greater noise detection and hence an increased data integrity checking overhead is required. To ensure error-free data transfer over a specific medium there is usually an associated data transfer technique. This can be thought of as a code or method for transferring data and is usually associated with the type of medium used. An investigation of these techniques associated with a wireless radio link is dealt with below. Concerning radio frequency there are many available methods, the most popular being Pulsed Code Modulation (PCM), Pulsed Width Modulation (PWM), Gaussian Minimum Shift Keying (GMSK) and Frequency Shift Keying (FSK) or a combination of these (Litwin, 1992), (Bedford, 1990a, 1990b).

For the purposes of this project it was decided that FSK was more than adequate for the communication process required. In this application it was suitable to employ low data transfer rates.

2.3.5 Frequency Shift Keying (FSK)

Frequency Shift Keying (FSK) is the most commonly used method for transmitting digital data over radio and telecommunication links. The digital high and low signals are replaced with predetermined distinguishable tone values. These values are modulated onto a carrier frequency and transmitted. Once received these tones are translated back to their respective digital highs and lows. The main advantage of FSK is its resistance to static and other noise interference. An appealing factor favouring this technique is its ability to communicate separately with more than one station without the need for intelligent interrogating. This is achieved by using the same transmission frequency and medium but allocating different encoded tones for the high and low signals. Using this method, unintelligent listeners can receive packaged data without the need to verify whether the data is intended for that specific listening station. When communicating with more than one intelligent listener, there is no need for different encoded tones because the intelligent receiving device can verify using some form of predefined header data whether or not the received information is intended for its use. Another method of communicating separately with more than one station is the use of a tri-state modem. Compared to the conventional bi-state modem which utilizes only two frequencies, the tri-state modem makes use of a third frequency, called a carrier frequency. This term should not be confused with the transfer mediums carrier frequency upon which these data transfer frequencies are superimposed. The tri-state modem selectively addresses each recipient, one at a time, by activating them with their respective carrier frequencies (Exar Integrated Systems, 1978). The tri-state modem was not implemented in this research project as there was only a single talker and listener operating on the modem at any time. The modem then communicates using the bi-state frequencies superimposed onto this carrier. A diagram showing output and FSK waveforms is given below. (Note: The phase-lock-loop has a finite 'locking time' and this is shown in the demodulated waveform below.)

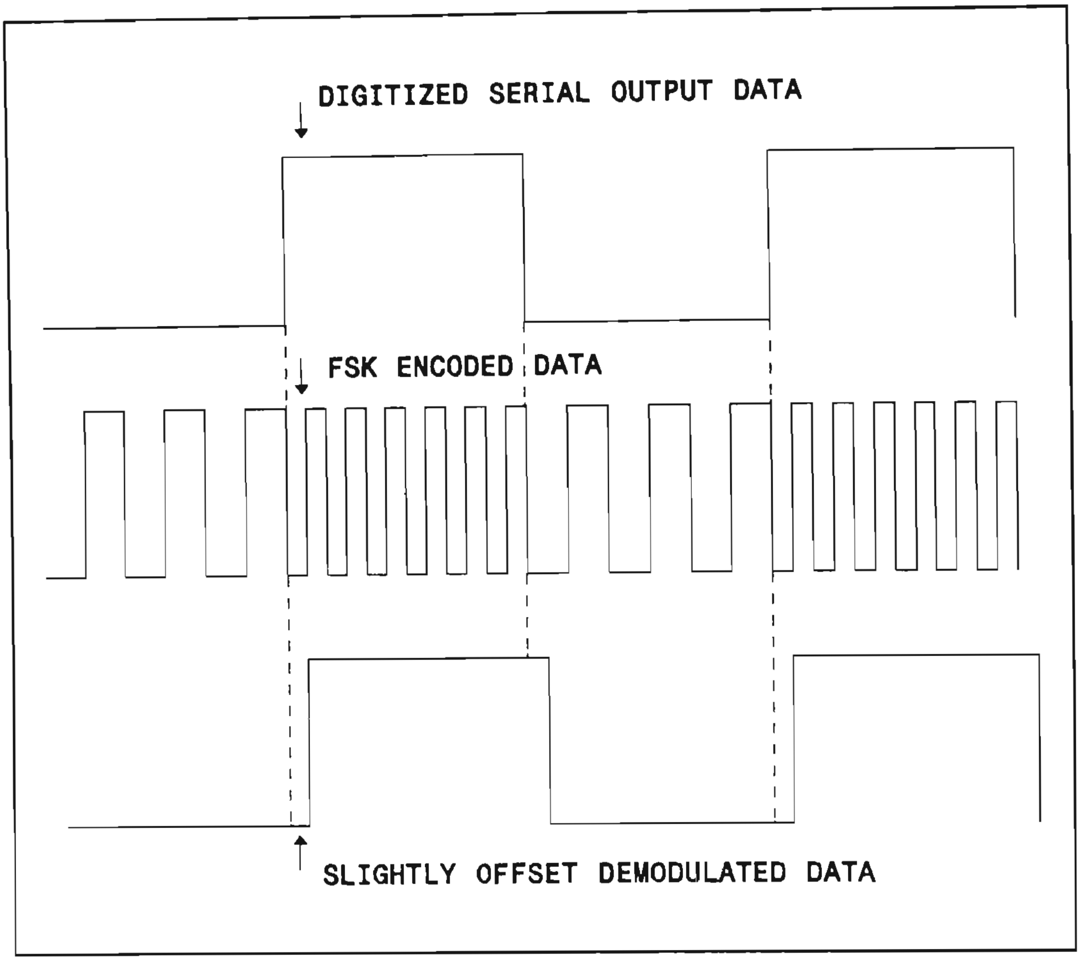


Figure 2-3: Example of Output and Tone Signals used in FSK

2.4 Standardizing Protocols for the Interconnection of Microprocessors

The initial task facing the pioneers of free-ranging vehicles was the need to establish an 'Industrial Standard' for computer interconnection. The main advancement in this field was the introduction in 1962 of the Electronic Industry Association's Standard E.I.A. RS-232 model for serial data connection. This was updated in 1969 to become RS-232C. This protocol has become a standard among IBM compatible computers and many other micro-computers. RS-232C was developed long before T.T.L. integrated circuits and consequently the voltage logic levels are not conventional +5 volt and 0 volt. Instead, they vary somewhere between +5 volts and +15 volts for a high signal and -5 volts and -15 volts for a low signal. In the manufacturing environment this facilitated a predefined common communication protocol, allowing for two-way communication between an intelligent AGV having an onboard micro-controller, and a CAP. This solution, however, did not satisfy the overall FMS requirements where a variation of intelligent devices were required to work homogenously. A manufacturing system controller can have many intelligent devices with which it must communicate. From this predicament a Manufacturing Automation Protocol (M.A.P.) emerged. This is designed on the basis of the International Standards Organisation Open Systems Interconnection (I.S.O./O.S.I) reference model.

The M.A.P. system is designed to enable a single cable to link different brands of computers, robotic assembly systems, and other intelligent devices, through a common communication protocol. This will eventually result in the ideal goal of homogeneity in communication within a FMS.

Together with this predefined hardware protocol a common character set was chosen, namely the American Standard Code for Information Interchange (ASCII). This defines a standard binary output associated with each character in the character set and is the most commonly used character set. It was initially developed in 1977 and defines 128 individual characters. Each character has an associated binary output consisting of 7 bits. The eighth bit was left for parity definition. It has become a world wide standard under several organisations. It represents all the capital and lower case letters, numerals and popular punctuation marks. (Another character set somewhat less popular is IBM's Extended Binary Coded Decimal Interchange Code - EBCDIC) (Leibson, 1989).

Using these defined standards, wireless data transfer between various intelligent devices can be investigated from a common perspective.

2.5 Description of the Design Communication System

The working environment utilized for this research application comprised a laboratory with dimensions of 4 metres by 7 metres. Due to constraints of benches and desks, the AGV has a free working area of 2.7 metres by 3.2 metres. In one corner of the laboratory the CAP workstation is placed. The path digitizing and AGV monitoring is all achieved from this point. A modem is connected to the workstation and also to the transceiver and this set-up accomplishes half duplex communication. (This is bi-directional communication with only one talker at a time). The vehicle working environment is marked out on the floor with tape. This facilitates physical measurement readings which are necessary when measuring navigational results. Navigational beacons are placed at locations within the environment and these are used for determining the navigational positional co-ordinates. On board the AGV a transceiver is connected to a modem which is in turn connected to the onboard microprocessor.

The medium used to transfer information between the CAP and the AGV is that of radio frequency and this is performed using two transceivers. They operate using frequency modulation at a 144700 kHz carrier frequency. Each of the microprocessors communicate via their respective RS-232C ports (Leibson, 1989). Data is transferred from these ports to an FSK modem. An FSK modem functions as an interface between a computer and a transceiver. On reception of data the modem firstly determines the integrity of the incoming signals. Provided that the incoming tones fall into the predetermined communication values, the modem supplies the data to the microprocessor's serial communication port. A subroutine is called which performs the task of data integrity checking and verification. One subroutine is used for transmitting data while another is used for receiving data. The configuration allows only one communication link at a time, but in both directions - this is known as dual simplex communication.

2.5.1 Medium

The medium used to transfer information between the CAP and the AGV is radio frequency and this is performed using two transceivers. Two transceivers were readily available for this task. These were Belcom, LS-20XE 2M FM transceivers. They operate on a selectable frequency modulation ranging from 140-150 MHz. A higher frequency would have been more appropriate in terms of RF obstacle penetration. These could be barriers such as concrete walls. Typical frequencies applicable to the manufacturing sector fall into the 400 MHz range. The specific frequency chosen for this operation is 144700 kHz. The transceivers operate from a 5 volt supply, the AGV obtains this power from the power board described in the section covering vehicle layout, and the CAP obtains power from a separate transformer. The use of frequency modulation as opposed to amplitude modulation presents the advantage of low static interference. Static interference is similar to a superimposed noise on the carrier frequency and this can result in sporadic errors (Watson, 1983).

2.5.2 Data Transfer Technique applied in this Project.

The modem is an electronic hardware device used for data transfer. The word modem originates from its combined function of modulating and demodulating specific tones used in typical voice functioning communication networks. FSK is the method whereby digital ones and noughts are translated into predetermined distinguishable frequencies (tones). These are then modulated onto a carrier medium. On reception of these frequencies at the receiver station, they are demodulated back into their respective ones and noughts. In other words, a modulator-demodulator is needed to translate digital ones and noughts into their respective frequencies and back again (Exar, 1978). The modem converts these digital ones and noughts into their respective frequencies using a tone generator. In this application, the noughts have a frequency of 1070 Hz and the ones have a frequency of 1270 Hz.

The carrier medium chosen is a 144 MHz FM radio frequency. The FSK frequencies are modulated onto this carrier and transmitted to a receiver. The receiving modem then demodulates these frequencies back into their digital form with a tone decoder. Radio transmission and reception is achieved with a Belcom LS-20XE FM transceiver. The speed of transmission is 300 bits per second (baud rate). This relatively low baud rate was initially chosen to reduce the possibility of interference. Figure 2-4 is a block diagram displaying the transceiver and modem configuration.

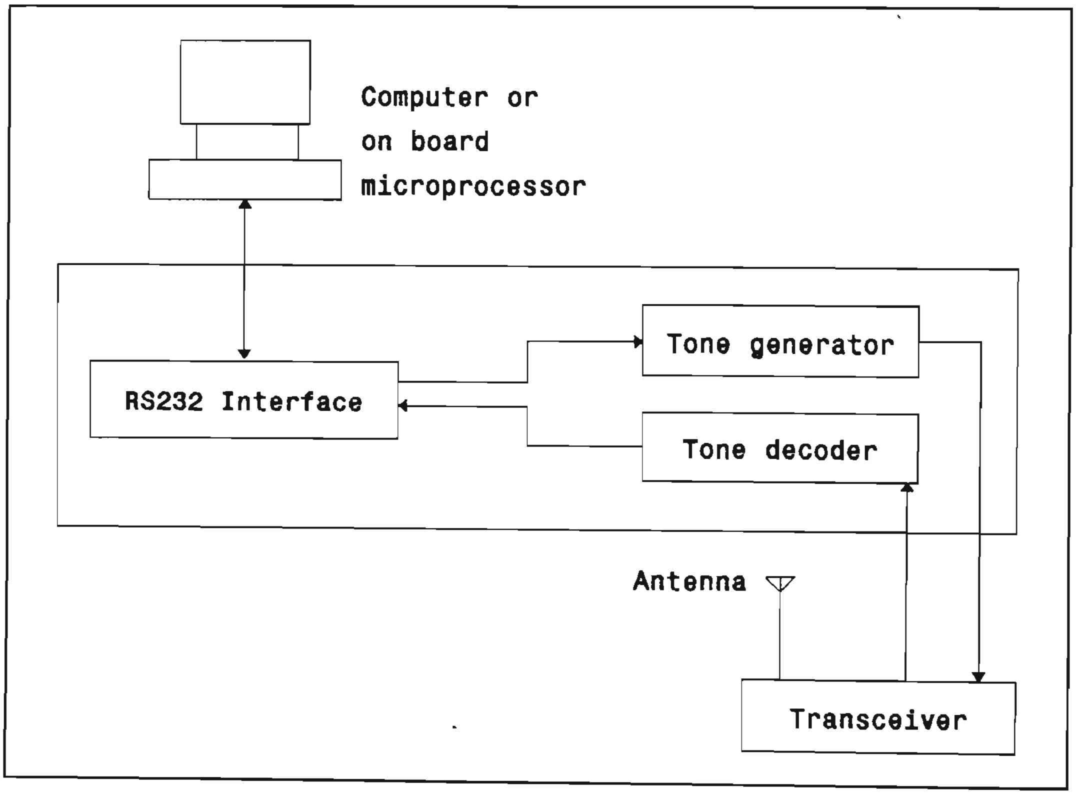


Figure 2-4: Block Diagram of Transceiver and Modem Configuration.

Photograph 2-1: Photograph of Transceiver and Modem Configuration.

An explanation of the modem construction is provided in Appendix I. Further details of the microcontroller interfacing and transceiver interconnection is provided. Upon completion of this wireless communication link, four data transfer tests were conducted. The initial test was to verify the transmission range in a direct line of sight between the transmitter and receiver. The second test subjected the communication link to a typical AGV working environment. The third test carried out investigated the transmission range through concrete barriers. A final test conducted examined the transmission range through concrete barriers when subjecting the communication link to machine interference. The above results are detailed in chapter five as part of the overall discussion of this research application.

CHAPTER THREE

GUIDANCE

3.1 Introduction

An AGV which is travelling within its environment is primarily required to avoid collision with obstacles such as other vehicles or machines. This is usually achieved by defining a mapping system which the AGVs must follow. When following these predefined paths, preset tolerances are required where a vehicle may deviate from its desired location. This vehicle movement, together with its predefined set of control conditions, is known as guidance. Guidance can be defined as the technique whereby a vehicle is given directions and motion instructions, satisfying a set of conditions such that it arrives at a requested location.

To avoid ambiguity, it is necessary to define the difference between conventional fixed path guidance and imaginary path navigational guidance. Fixed path guidance is the technique which requires the vehicle to follow a predefined hardware constructed route. This guidance is not compelled to identify its positional co-ordinate location within the working environment. Contrary to this, imaginary path navigational guidance requires some form of positional determination. The term navigational guidance is not to be confused with the conventional understanding of guidance which is conceived as the following of physical predetermined fixed paths. For navigational guidance positional co-ordinate points are compared with software specified points which make up imaginary guidepaths. Using computational control algorithms the vehicle can be manoeuvred and positioned. Robins (1986) of General Electric Projects Limited defines navigation simply as 'Where am I?' and navigational guidance as 'Which path do I follow to arrive at my destination?'. For clarity concerning this research application the term navigational guidance is defined as the algorithm and guidance procedure dictating the movement of the AGV to its requested location.

Having established the above definitions, this chapter begins with an account of the various fixed path guidance techniques and navigational guidance techniques. Details of the mosfet motor controller designed for this research application are provided. A digitised mapping structure to define AGV routes in a working environment is presented. The various guidance techniques which have been implemented in AGV movement are investigated. Once these techniques are established, an explanation of the navigational guidance algorithm that satisfies course and fine navigational guidance requirements is given.

Some guidance techniques incorporate two or more forms of navigation. For purposes of this research application a procedure was developed whereby course and fine position definition was incorporated using a single navigation technique. The guidance criteria therefore established the navigational tolerances. The nature of the navigational technique implemented indicates that the accuracy of the navigation system is dependent on the speed of the vehicle. As a result of this, course navigational tolerances were defined for a travelling vehicle and fine navigational tolerances for a docking vehicle. This concept of course and fine navigation is implemented using two separate navigational techniques (Burhanpurkar, 1991), (Petriu, 1991). This is demonstrated by Banta (1989). They cite an example where a combination of dead reckoning and position measurements has been researched. Another method employing a dual guidance technique is evidenced in laser guidance and dead reckoning (Evans, 1988).

3.2 Overview of the Fixed Wire Guidance Techniques

When AGVs were initially developed, there was little requirement for flexibility due to the then rigid manufacturing structure. The basic requirement was for AGVs to move from one location to another along a predefined set path. AGVs followed these paths using discrete electronics or mechanical hardware for tracking and guidance. Examples of the more commonly adopted methods for path determination that have been developed are presented.

3.2.1 Induction Guidance Method

Most AGV industrial suppliers use the induction guidance method for vehicle movement. This method usually implements an 8 millimetre wire embedded approximately 25 millimetres underground. This wire is laid along all the desired AGV travel routes and typically employs a low voltage alternating current with a frequency ranging from 9 kHz to 32 kHz. This current induces a detectable low strength electro-magnetic field around the wire. This magnetic field is picked up by sensing coils onboard the AGV. The deviation of the vehicle from the induction wire is directly proportional to the induced strength in the receiver coils. These sensors also determine the polarity of the electro-magnetic field and thus the direction of travel. The received information is amplified and translated into guidance signals which are used to manoeuvre the vehicle along the desired path. When using this form of guidance the induction wire may also be used to communicate with the vehicle. Higher frequencies are superimposed onto the standard induction frequency. The data is usually transmitted using Frequency Shift Keying (FSK) and then decoded onboard the AGV. Communication is usually accomplished in one direction, with the controlling computer sending signals to the AGV. This single direction communication is known as simplex communication. Two way or duplex communication using a guidance wire as a transmitter and a receiver has been accomplished. However, communication from the AGVs has proved problematic. This occurs as it is difficult for the AGV to transmit a signal of sufficient strength into the wire guidepath. This method of guidance incorporating two-way communication has been developed by Dayal, Rao & Sen (1986). Two major drawbacks are that firstly, paths are not easily modified because of the buried cables; secondly, the initial installation costs are high.

3.2.2 The White Line Guidance Method

Routes are mapped out using a broad white tape laid down along the desired vehicle path. Optical sensors on either side of the vehicle are used to track this white line. Deviation from the track is thus optically monitored by the amount of reflected light received by the optical sensors. This reflected light strength informs the guidance of deviation from the desired path. This system allows for a flexible economic way of quickly defining and monitoring vehicle routes. A clean environment is essential for this system and is therefore ideally suited for electronics installations and office environments. A guide path encoding technique has been developed to upgrade existing optical guidance methods. This can increase the flexibility of existing fixed path vehicles allowing them to enhance some flexible guidepath properties. Using this technique vehicles may depart from their fixed paths when encountering unexpected obstacles or for delivery in more remote areas of the working environment (Petriu & Basran, 1989).

3.2.3 Chemical Path Guidance Method

This is similar to the white line method. Here, instead of a white line, a chemical substance is laid down in a trail along the vehicle path. This is usually in the form of an invisible fluorescent dye approximately 2.5 centimetres wide.

The AGV tracks this path by focusing an ultraviolet light source onto the substance. The reflected beam is monitored with optical sensors and these inform the guidance circuitry of any deviation from the desired path.

The above two guidance methods are almost identical and therefore have similar disadvantages:

i) Networks must be kept fairly simple, since junctions cause complex guidance problems.

ii) Due to the nature of vehicle tracking, these systems are sensitive to dirty environments. This causes interference for the tracking sensors.

iii) The exposure of the tracking lines to the working environment causes path wear and tear. It is found, however, that these lines need repainting every six to twelve months.

iv) Lines may be obscured by objects which will hinder or halt the guidance.

3.2.4 Metallic Strip Guidance Method

Metal strips are laid down along the vehicle path in a similar manner to induction guidance. Sensors are used to track these strips. This method has the advantage of being applicable in a harsh dirty environment whilst still maintaining relatively good flexibility.

The major disadvantages of this system are:

i) Networks must be kept fairly simple, since junctions are not as easily manoeuvred as with wire guidance.

ii) This method cannot be used in a machining environment where metallic shavings could possibly interfere with the vehicle tracking.

iii) The maximum detecting distance of the magnetic induction sensing devices is approximately 25 millimetres which minimizes the vehicle undercarriage clearances.

iv) Objects lying on top of the metallic strip may hinder or halt the guidance.

3.2.5 Magnetic Marker

Magnet arrays are placed at predefined locations along an AGV route. Sensors are located onboard the AGV and these determine the polarity and number of positioned magnets. Using the polarity, number and positioning of these magnets, guidance and position recognition is established. The main drawback of this method is contamination due to iron filings on the magnets. This causes incorrect positional readings. A method of magnetic guidance has been researched whereby a belt-like magnet is laid down along the desired AGV route and sensors onboard the vehicle are used for tracking (Kamewaka & Uemura, 1987).

Although by the late 1980's it was found that the induction guidance technique was the most favoured, conventional guidance techniques were becoming limited. As AGVs progressed, collision avoidance and congestion problems arose, which initiated complex software guidance algorithms. Vehicle trafficking difficulties stemming from the undynamic nature of the AGV systems and the lack of a two-way communication network became more pronounced. This revealed the need for a more flexible materials handling system.

The introduction of computerised machines and automation has promoted the requirement for a more flexible transportation network. AGVs have evolved to the point where predefined physical tracks are undesirable and there is a need for an autonomous navigation system. Without a predefined physical path such as a guidance rail, an AGV could have the ability to roam freely in its environment. This increased flexibility would permit vehicle routes to be altered in real time. This means that path alteration on a CAP would be immediately transferred to the vehicle. This then would ideally suit the diverse requirements of a fully integrated manufacturing environment. Using these concepts, a navigation system is required to define a vehicle's location. Once a vehicle position is determined, a guidance algorithm defines a travel path between the navigational position and the desired destination. This path planning is known as navigational guidance. Navigation techniques are being researched using various types of wireless sensory transducers. These techniques are used for guidance of free-ranging AGVs and fall broadly into the following categories.

3.3 Overview of Imaginary Navigational Guidance Techniques

3.3.1 Inertial Navigational Technique

This technique utilizes gyroscopes to detect vehicle movement. This is accomplished by monitoring the change in acceleration. Gyroscopes are set up with their axes parallel to the direction of vehicle motion. If the vehicle deviates from its path, an acceleration perpendicular to the direction of travel will be detected on the gyroscope. This acceleration value is integrated twice and this yields the positional deviation from the path. These deviations are sent to the guidance controller for path correction. A disadvantage of this method is that a gyroscope monitors change in acceleration and if a vehicle is travelling at constant acceleration, path deviation cannot be detected. (Turpin, 1986) (Miller, 1987)

This form of navigation was applied in the aerospace industry for many years. As this application was costly it was not popular in the industrial sector. In 1985, the first inertial guided system for industrial application was introduced by Flexible Manufacturing Systems Inc. The first test system was used in the electronics industry for silicone wafer fabrication (Miller, 1987). Further advancements in technology and reduction in costs has generated some interest in navigation applicable to the manufacturing sector.

3.3.2 Dead Reckoning Navigational Technique

This method employs encoders to monitor the rotation of each wheel. Using this information, the relative position of the vehicle is calculated with reference to its starting point. However, wheel slippage is difficult to measure and therefore errors can accumulate if this is not assimilated with another form of guidance. An original method overcoming some of the problems of accuracy and slippage has been developed by Cybermation (Miller, 1987). A single steering motor is used to control all wheel assemblies in such a way that all the wheels steer in the same direction at all times. All the wheels trace parallel paths and therefore no differential or slippage is experienced. This provides excellent tracking capability while eliminating the problems associated with differential alignment. This dead reckoning method is used on the K2A mobile platform in conjunction with their ultrasonic imaging technique (Miller, 1987). A method of determining a real-time vehicle position by implementing a pseudo-random binary sequence has been researched. This technique, although effective, still relies on dead reckoning for navigational determination (Basran, Petriu & Groen, 1989). A further experimental model has been tested to evaluate linear and rotational movement of an AGV. Tests conducted resulted in a linear accuracy of 0.25 percent and a rotational accuracy of 0.4 degrees (Culley & Baldur, 1988).

3.3.3 Ultrasonic Imaging Navigational Technique

Ultrasonic distance meters are used to measure the distance between the vehicle and its surroundings. An image map of the vehicle work area is digitized and stored in onboard microprocessor memory. Onboard ultrasonic distance meters measure the distance from a known vehicle position to its direct line of sight surroundings. The onboard microprocessor then continuously generates a current map of its surroundings. This map is compared with a predefined reference map and through this comparison the AGV is able to estimate its current position. This comparison procedure has been developed exploiting artificial intelligence in order for the navigating vehicle to efficiently arrive at its predefined goal (Murphy & Arkin, 1988). Cyberworks use this technique in their commercially available AGVs (Burhanpurkar, 1991). Dedicated navigational integrated circuitry, developed by Cyberworks, embodies all the artificial intelligence, vision, processing, navigational algorithms and motion control for autonomous AGVs. A curved ultrasonic array transducer has been investigated. This employs an original technique whereby 32 transducers are placed in an array. The received pattern is then compared internally with an image map of the surroundings. From these comparisons, positional determination is attained (Huissoon & Moziar, 1989). A transmission line matrix method of modelling wave propagation has been implemented to evaluate ultrasonic imaging of a workspace. This application provides an improved understanding of the interaction of ultrasonic waves and their targets (Pomeroy et al., 1991).

One of the major disadvantages of this form of navigation is the requirement for powerful computational and data storage facilities. Ultrasonic distance meters are susceptible to interference from manufacturing machinery. This is especially the case with commercially available standard ultrasonic transducers that operate in the relatively low 40 kHz bandwidth. High frequency transducers that operate around the 200 kHz bandwidth, while becoming commercially available, are expensive. These factors need to be taken into consideration during system design and implementation because they depend on the AGV’s application and environment.

3.3.4 Optical Stereoscopic Vision

Two onboard video cameras are used to view the same stationary object, from which the angular disposition is measured. The two cameras are located onboard the AGV at predetermined distances allowing them to generate two different images of the same object. A comparison is then made of these two stereoscopic images of the object, from which an algorithm determines the vehicle position. An imaging technique utilizing minimal computing overhead is demonstrated in the VISOCAR. In this application the navigational requirements are broken down into criteria specific to each area of navigation. This is similar in comparison to the concept of course and fine navigation (Frohn & von Seelen, 1989). Another technique utilising stereoscopic obstacle detection and which implements a topographic mapping method, termed the inverse perspective mapping technique, has been developed. Minimal computing overhead is attained here by utilising algorithms that discard irrelevant obstacle information (Mallot, Zielke, Storjohann & von Seelen, 1991), (Storjohann, Zielke, Mallot, von Seelen, 1990).

3.3.5 Optical Navigational Technique

Optical navigation uses techniques involving some form of light source to determine vehicle position. There are numerous forms of optical guidance available and therefore a standard technique is difficult to define. Light transmitting beacons are historically well known for optical navigation, for example, the use of lighthouses. This rudimentary navigation form uses different light pulses to determine the location of beacons. Experiments using these concepts of pulsating visual light beacons have been conducted to determine their applicability for AGVs within the manufacturing environment (Katz & DeWet, 1990). However, most practical AGV applications in the manufacturing environment use infrared as a light source because of its immunity to external interference and the fact that it is not visible to the naked eye. This results in an invisible but effective method of signalling between a vehicle and a fixed location point. Using this signalling technique many methods of optical navigation have been conceived for practical application within the manufacturing sector. For instance, a practical application using a reflective light system was developed by the TOR group (Quebec, Canada). The AGV directs infrared light towards reflective targets and the return signals are triangulated. This advises the vehicle of its relative position (Premi et al., 1983). Retroflective materials and their application for AGV guidance has been investigated (Dickerson, Lee, Lee, Single & Li, 1991). A further advancement noted in this field is a rotating laser scanning device produced by the General Electric Company in conjunction with the Caterpillar company. Navigation is achieved by this laser monitoring the return signals from bar code targets placed within the navigation environment (Evans, 1988), (Butler,1989). An original navigation technique has been developed incorporating ultrasonic and optical sensors in a free-ranging navigation system (Drunk, 1988).

Over the past few years, as the interest in wireless navigation expanded, the above techniques began to be more thoroughly investigated. As this is a new science, no single navigation technique has yet proved itself for application within the manufacturing environment. All these navigation techniques, like their fixed physical path predecessors, have advantages and shortfalls as far as flexibility, ease of installation, low cost, range and accuracy are concerned (Voskiakos & Malis, 1990). Speculation exists that further experimental work in the navigational field will result in the preferred technique for application within the manufacturing environment. This supposition is based on the evolvement of fixed wire guidance which resulted in the induction wire technique being the most utilized.

It is felt that optical triangulation offers the most benefits by comparing flexibility, ease of installation, low cost, range and accuracy for application within a manufacturing environment.

The nature of navigational guidance demands that a guidance strategy should first be defined. It is necessary to clearly specify the guidance method by defining the overall design criteria which includes the drive mechanism, mapping structure and guidance rules. This lays the basis for the development of an original navigational technique, details of which are given in chapter five.

3.4 Guidance Design Criteria

The conventional AGV, designed for materials handling, is based on an inflexible guidance system which incorporates fixed guide-paths (Dillman & Rembold, 1988). The AGV is a computer-controlled system, therefore, its integration with a hierarchical type of computer-controlled manufacturing environment is both possible and advisable. Linking a flexible AGV system with FMS hardware could generate 'islands of automation' (Arkin & Murphy, 1990), (Hartley, 1984). This could serve the envisaged dynamic requirements for modernised manufacturing (Katz & Asbury, 1990). Increased flexibility, autonomy and integration within a manufacturing environment has resulted in the development of AGVs into free-ranging vehicles. A free-ranging vehicle, serving as a materials handling system or base for mobile robots, eliminates the present rigid guide paths. Furthermore, this enables on-line vehicle positional determination and amendments to predefined imaginary routes (Katz et al., 1990).

For flexibility, the guidance system requires overall positional control of the AGV. The speed and direction requirements of the AGV must be satisfied at all times if the vehicle is to be truly free-ranging. A free-ranging AGV must incorporate some form of computational navigation guidance algorithm (Fok & Kabuka, 1991), (Kim, Young-Gon & Naganathan, 1990). In order to determine meaningful movement an AGV should have a desired requested location and a known real location. The angular and linear difference between these two positions results in calculations necessary to ascertain guidance. Algorithms are required to determine variables such as time and rate of acceleration, velocity and wheel direction. These calculations consider predefined guidance routes and then implement control functions to achieve the desired requested location. In most guidance techniques, the error between the desired and known position is continuously interrogated and corresponding action taken until this error is less than that set out in the guidance criteria.

For AGV autonomy, guidance forms an integral part of navigation and one cannot function properly without the other. These two work in a closed-loop feedback concept; the guidance continually corrects the error between navigation position and desired position. This is demonstrated in the block diagram below.

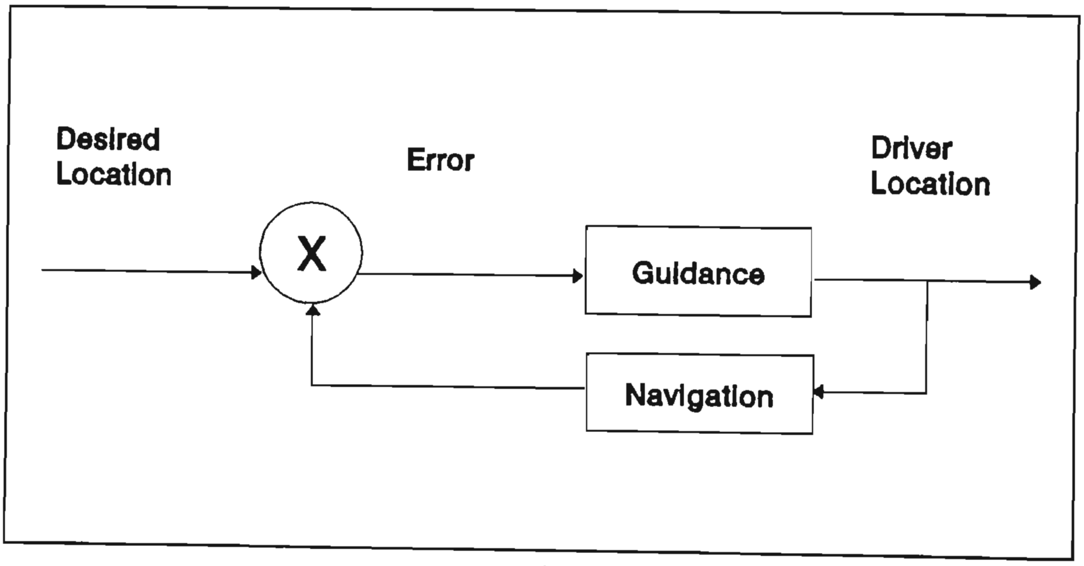
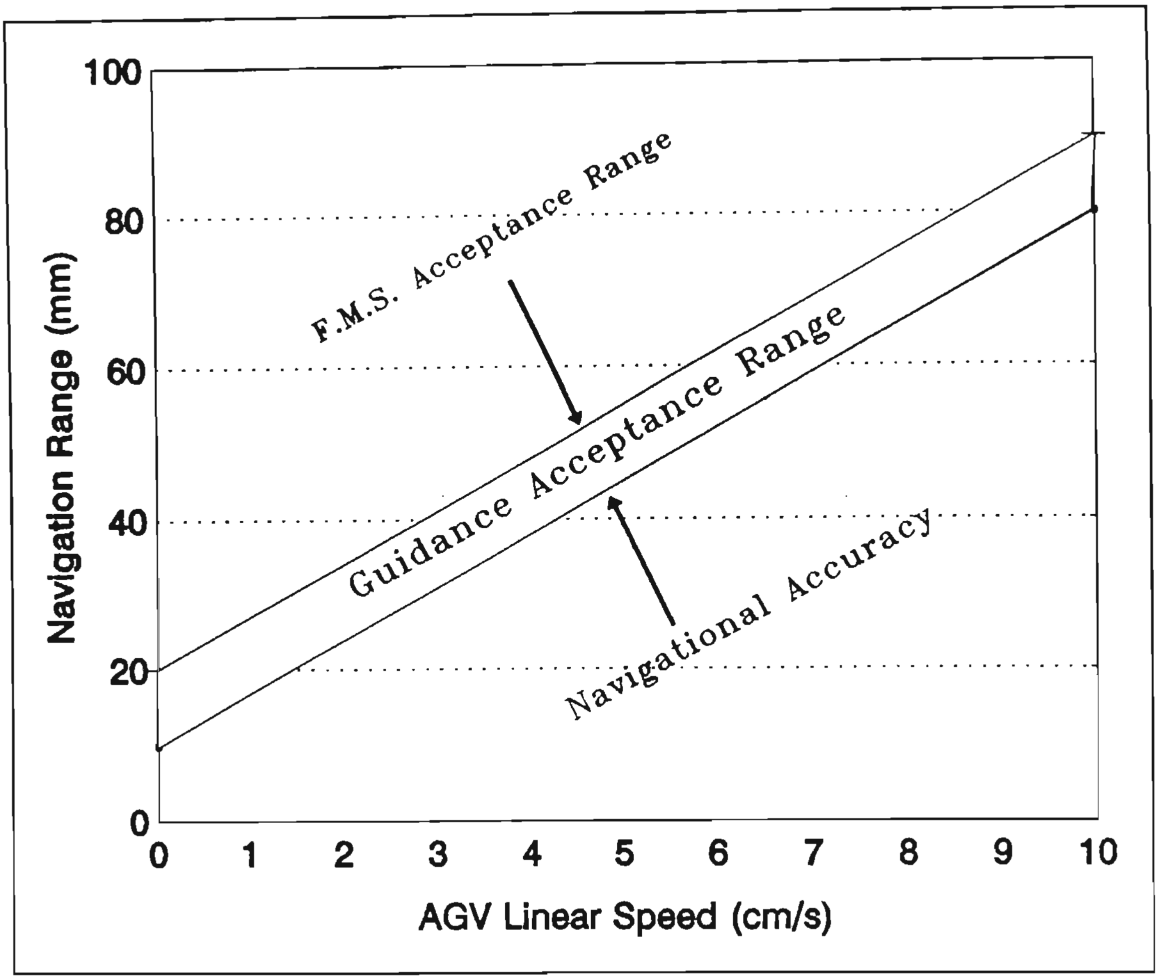


Figure 3-1: Flow Diagram of Navigation and Guidance in Feedback System

For an AGV working in a FMS two main design criteria have to be satisfied. The dynamic and static tolerances of the vehicles guidance have to fall within the overall FMS acceptance range. The dynamic guidance tolerance is the allowed deviation of a travelling vehicle, from a pre-mapped path, before corrective guidance action is initiated. Dynamic accuracy of the navigation system is the main criteria when considering this tolerance value. If an acceptance range equal to or smaller than the dynamic navigational accuracy is required then the guidance would continually overcorrect the positional accuracy resulting in an unstable system. This applies similarly to the static accuracy. The static guidance acceptance range must be greater than the static navigational accuracy if a vehicle is to successfully position itself without continually overcorrecting. The graph below defines the navigational accuracy for a given linear speed together with a FMS acceptance range. The guidance acceptance range should fall into the area between these two graphic representations if desired movement is to be achieved.



Graph 3-1: Example of a Graphic Representation for Acceptable Guidance Limits

An examination of the above graph indicates that if the FMS navigational acceptance range is less than the navigational accuracy then the guidance acceptance range would not exist. Under these conditions if guidance is implemented the AGV guidance would continually overcorrect resulting in unstable control. The implementation of a poor navigation system in comparison to the requirements of the FMS would again result in an unstable system.

A vehicle attempting to position itself at a desired location must firstly examine its static location by interrogating the navigation system. The guidance algorithm compares this information with the desired vehicle position and whenever this position falls outside the guidance acceptance area corrective action is taken.

The design criteria of this research application required that a free-ranging AGV must be able to follow a predetermined mapped path within a manufacturing environment. This path can be modified according to specific requirements without having to rely on a predefined physical path for its movement. The mapping of predetermined paths is performed via the CAP, including restricted areas of access, obstacle avoidance and intermediate operations (Cesarone & Eman, 1989). Subsequent to such path and area mapping simulation, the data is both stored and downloaded on request to the AGV's on-board microprocessor.

Having specified the guidance criteria it is necessary to detail the integration of this to the AGV hardware.

3.5 Guidance Hardware

In this section a description of the drive mechanism used to manoeuvre the vehicle is presented, as well as details of the design and construction of the electronic d.c. drive circuitry. This is followed by an explanation of the interface between the electronic motor driver hardware and the micro-processor. Finally, the method for structuring a simulated vehicle environment is outlined. This includes path and obstacle definition.

3.5.1 The Drive Mechanism

The Mecanum movement principle chosen to move and guide the vehicle required that each of the four motors have independent speed and direction control. The kinematic analysis and implementation of a Mecanum wheel is reviewed and investigated by Dillman et al. (1988). The direction and movement of the vehicle was controlled by varying the speed of the wheels independently. This principle achieved optimum vehicle direction control satisfying all possible directional requirements of the guidance algorithm. (Dillman et al., 1988)

Motor control was achieved using mosfet d.c. chopper circuitry. An independent d.c. mosfet chopper was dedicated to four separate driver motors. This resulted in separate power control to each wheel. Double-pole double-throw relays are used to reverse the polarity of each motor. Each relay was energized using four digital outputs from the AGV motherboard. These determined the direction of each wheel and were managed by the guidance software contained in the AGV guidance subroutine. Four analogue outputs from the motherboard controlled the chopper driver power output to each motor. This resulted in the onboard guidance software controlling the chopper module and this drove each motor independently at varying speeds and directions of rotation. Full detail of the mosfet chopper module is detailed in Appendix I. A block diagram is presented in Figure 3-2 below. (Freeman, 1979), (Van der Horst, 1987), (Coughlin & Dirscoll, 1987).

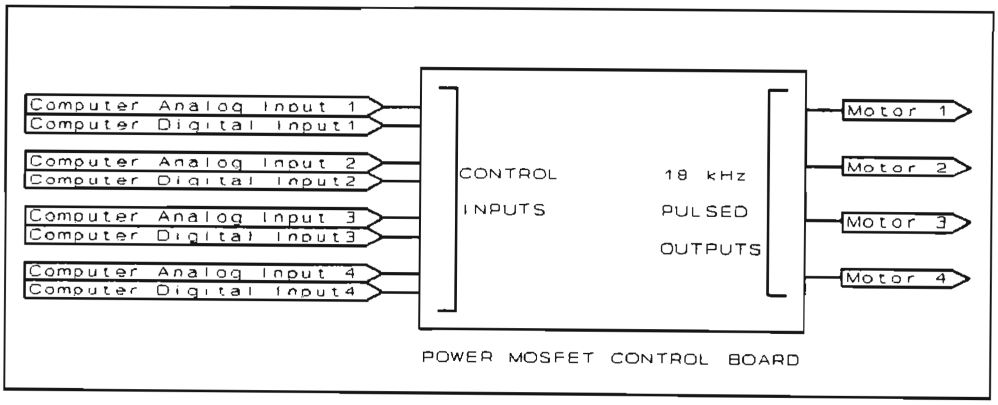
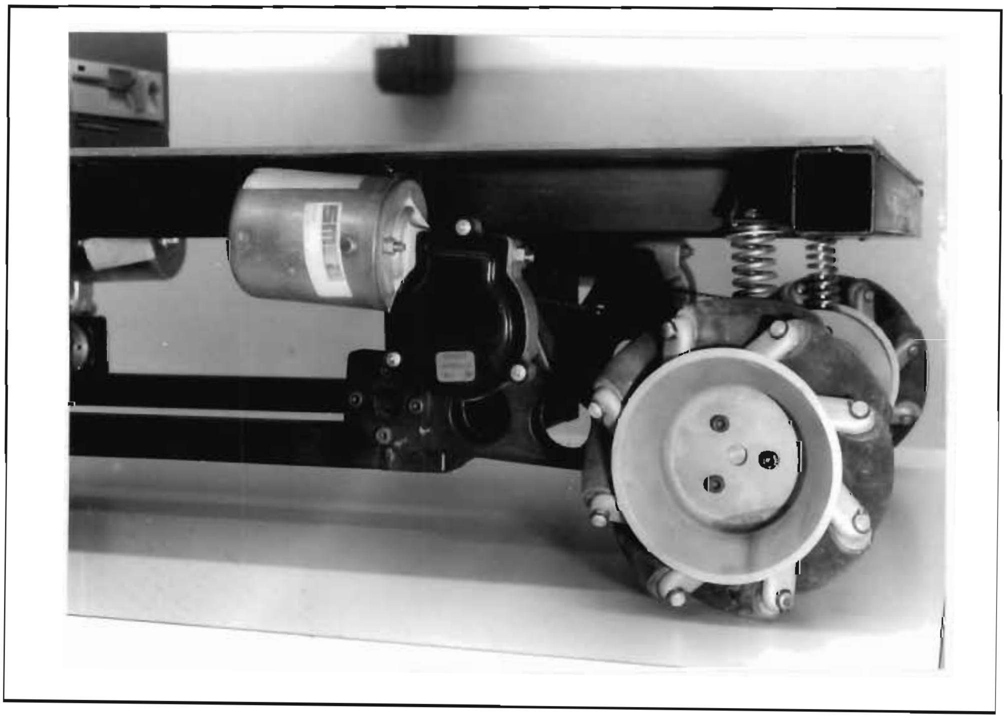


Figure 3-2: Block Diagram of I/O for Mosfet Chopper

The d.c. motors independently drove four wheels through a 5:1 ratio. These wheels were omni-directional based on the

Mecanum movement principle and measured 14 centimetres in diameter (Dillman et al., 1988). The wheel structure allowed the vehicle to travel in any direction specified by the user by varying the motor speeds and motor directions for each wheel independently. Each motor delivered a maximum of 1 newton meter when drawing 2.5 ampere. A top speed of 70 rpm was attained from each motor resulting in a maximum linear vehicle speed of 0.1 metres per second. A photograph of the Mecanum wheel and the d.c. motor is presented below.



Photograph 3-1: Photograph of a Mecanum Wheel and d.c. motor

Having established the drive mechanism the control strategy is now explained.

3.6 Computerized Mapping System

The computerised mapping system was developed to enable the AGV to move about the factory floor independently (Nielsen, 1988). The objective of obtaining a truly free-ranging AGV within a predefined work area was achieved by defining a map layout contained within the AGV microprocessor memory and on the CAP. This environment structuring consisted of defining paths which may be taken by the AGV within the given environment as well as prohibited areas. This allowed for areas which the AGV may access but are not on the predefined path layout. This defined a format whereby a location lying outside the predefined path structure could be accessed by the AGV. The function allowed the AGV to be free-ranging within the entire working environment.

The process of mapping and data manipulation for the correct motions is as follows: The length and breadth of the working environment is recorded. An algorithm then converts these dimensions into a grid-vector array. The working environment can then be viewed on the CAP. Areas where the vehicles may not pass are laid down on the screen with the aid of a digitizer. These areas are then erased from the vector array. The simulated mapping system is laid down within the working vector array environment which consists of lines and rotation points. Each path structure is verified to ascertain whether it falls within the pre-described vector array. Should the path fall outside the vector array, an error message is generated. Once all paths have been simulated on the CAP screen, the data is stored and downloaded to the onboard microprocessor.

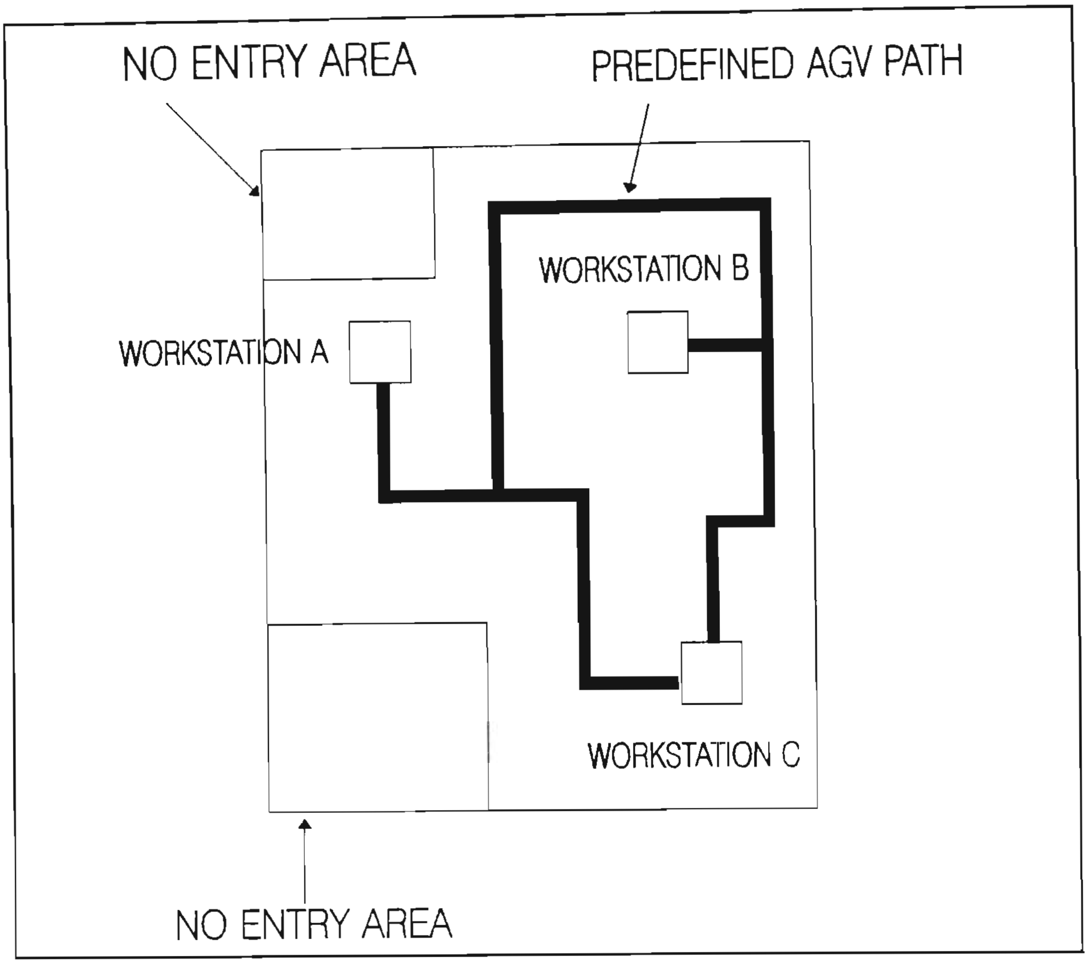


Figure 3-3: Schematic Representation of AGV Working Environment Displayed on CAP Computer Screen

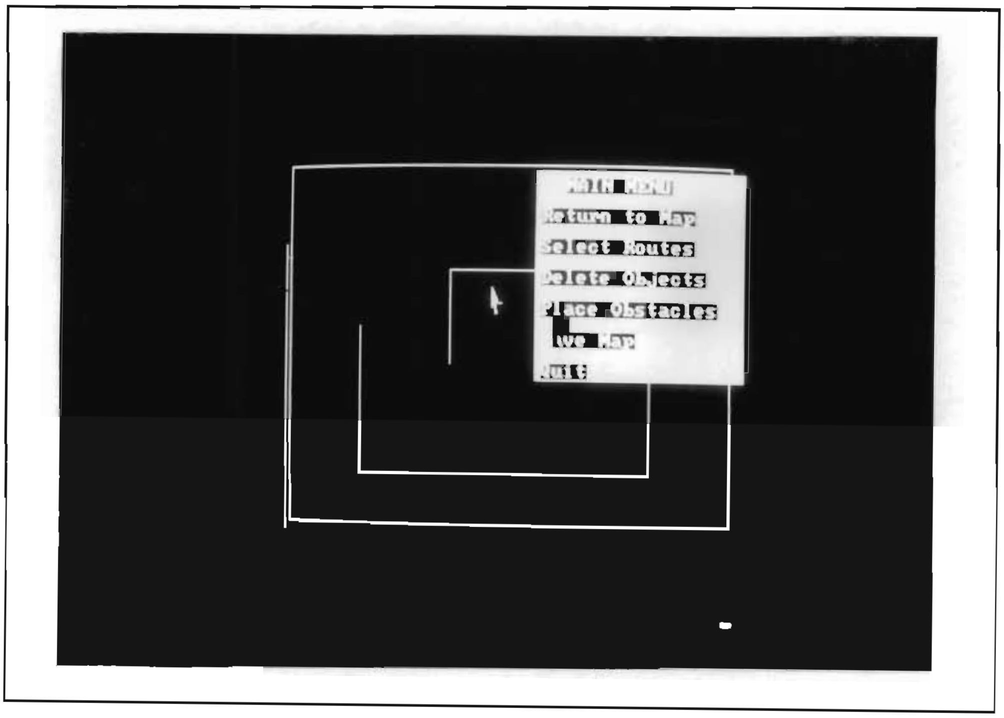
3.6.1 Central Program

A control program which integrates facets of design and control of a materials handling system has been developed and is presented. This program is divided into two main sections, namely: Real time simulation and dynamic interactive structuring of a materials handling environment. These are two separate strategies which are integrated into an overall central program used to facilitate dynamic path modification during real time vehicle operation (Moslier & Schneider, 1988).

The bulk of the mapping program structure consists of six subroutines. Each subroutine is operable from a selection menu which is located in the main control program. These routines can be independently selected using the digitizer. The main program displays the working environment upon which a pull down menu is overlaid. This menu displays those options which are used to simulate the working environment and control the operations of the AGV. This pull down menu is removed whenever the simulated AGV environment is required for display. Removal of this pull down menu is necessary for structuring the AGV working environment, modifying the routes or monitoring real time AGV movement. The six options located on the pull down menu are briefly described. Further details of each function and their associated subroutines are presented in Appendix I.

Upon installation of the AGV simulation package an operator is required to define an environment structure. Predefined routes can be laid down within the simulated environment using the 'select routes' option. Areas that are inaccessible to the vehicle due to physical obstructions such as machines or other impediments can be defined within the working environment using the 'place obstacles' option. Any routes or no-entry zones may be deleted using the 'delete objects' option. The structured environment can be saved to disk and downloaded to the AGV onboard microprocessor's magnetic media with the 'save map' option. Once a mapping structure has been defined real time simulation may be monitored. This is achieved by selecting the 'return to map' option. This option displays a simulated working environment on the CAP screen as well as the navigational co-ordinate points of the AGV as it manoeuvres along a predefined route. The screen layout of this simulation is depicted in the photograph and diagram presented below.

The simulation program presented provides the operator with an opportunity to alter path segments during vehicle operation. Any path segment may be altered to suit a dynamic operation requirement. This alteration can be achieved provided that the vehicle is not traversing the specific segment during the modification procedure. If modification is attempted on the same route segment that a vehicle is traversing, an error signal will be emitted and route alteration prohibited.



Photograph 3-2: Diagrammatic Representation Showing Graphical View of Controller Program

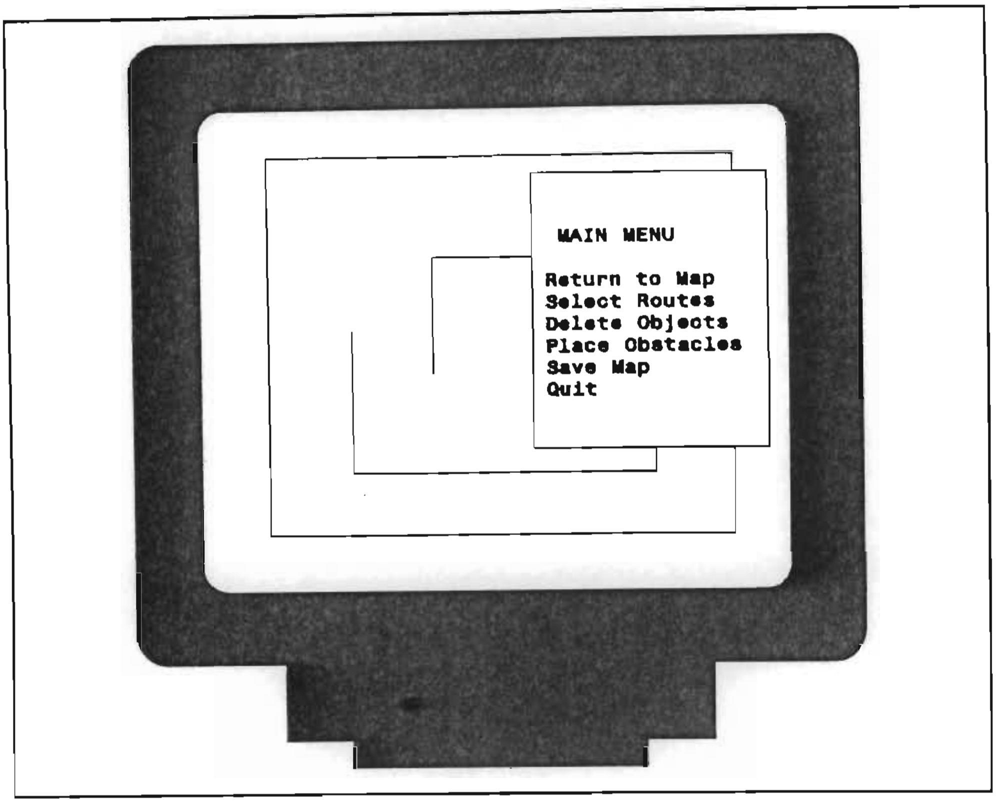


Figure 3-4: Diagrammatic Representation Showing Graphical View of Controller Program

3.7 Guidance Strategy

The AGV navigation system continuously updates the CAP of its co-ordinate position. This occurs whether the vehicle is stationary or moving. Using continually updated positional co-ordinate points, a vehicle path may be described. Furthermore, each predefined route segment can be defined as a vector with starting co-ordinates and ending co-ordinates. Using this data a navigational guidance strategy may be determined by comparing these navigational co-ordinates with a predefined AGV route segment. Over the past few years many navigational guidance strategies have been developed to facilitate effective vehicle movement. Artificial intelligence incorporating self-organizing, fuzzy logic controllers and associative memory type neural nets have been implemented in adaptive decision strategies for AGV guidepath control (Brown, Fraser, Harris & Moore, 1991).

It is considered that in most applications vehicle positioning requires an accurate navigation system and guidance algorithm. Static navigation is primarily concerned with vehicle docking. A vehicle attempting to position itself will manoeuvre at a minimum speed. For guidance purposes, the vehicle should take static navigation readings before finally positioning itself. This would result in a higher vehicle positional accuracy. AGV movement along a given path usually allows for greater tolerance limits. These greater tolerance limits enable the navigation system and associated guidance algorithm to operate within a greater working range.

For these reasons two separate guidance algorithms and associated guidance ranges are defined. The first algorithm is implemented in dynamic manoeuvring, the second to locate the vehicle. Although a guidance algorithm could be derived that would be dependent on varying vehicle speed, it is considered unnecessary for a general application. In most materials handling operations an AGV is required to travel along a given path and then position itself at an end location. In these applications a single dynamic algorithm would suffice for vehicle movement. A separate static algorithm could then be used for vehicle docking.

Guidance is effected by comparing navigational co-ordinates with a predefined AGV route segment. The vehicle route segments are stored onboard the AGV in a vector format. This reduces the guidance specifications to straight lines and rotations about the centre of the vehicle. Graph 3-1 illustrates that if the appropriate control is to be achieved then the guidance range should fall between the acceptable working environment range and the navigational accuracy. As the research vehicle does not have a defined environment range, the vehicle guidance range was defined to be

25 percent greater than the navigational accuracy. The navigational accuracy is determined from experimental measurement in chapter five and these results ultimately determine the guidance acceptance range.

The criteria for guidance stipulates that when a vehicle falls outside the predefined ranges, the appropriate guidance algorithm should be implemented to correct this deviation. The appropriate guidance algorithm is selected according to criteria based on the final navigation point of a given route. If the AGV falls outside the predefined range of the end location point then dynamic guidance is implemented. Whenever the AGV is within the predefined range of the end location, static guidance is implemented.

3.7.1 The Navigation and Guidance Interface Subroutine

In the event of an AGV navigational co-ordinate falling outside the predefined guidance tolerance limits, the main guidance subroutine selects either a static or dynamic guidance algorithm. The dynamic guidance algorithm is implemented in vehicle manoeuvring along a predefined route segment. Alternatively, the static guidance algorithm is implemented for vehicle positioning and docking.

The guidance is effected by continuously comparing the measured navigational readings with the desired path position. If the difference between these values is greater than the predefined dynamic guidance range then the corrective dynamic guidance routine is initiated. Upon the vehicle arriving within a predefined range of the requested destination, a locating guidance subroutine is implemented to position the vehicle at the desired end point. This procedure is illustrated in the flowchart below.

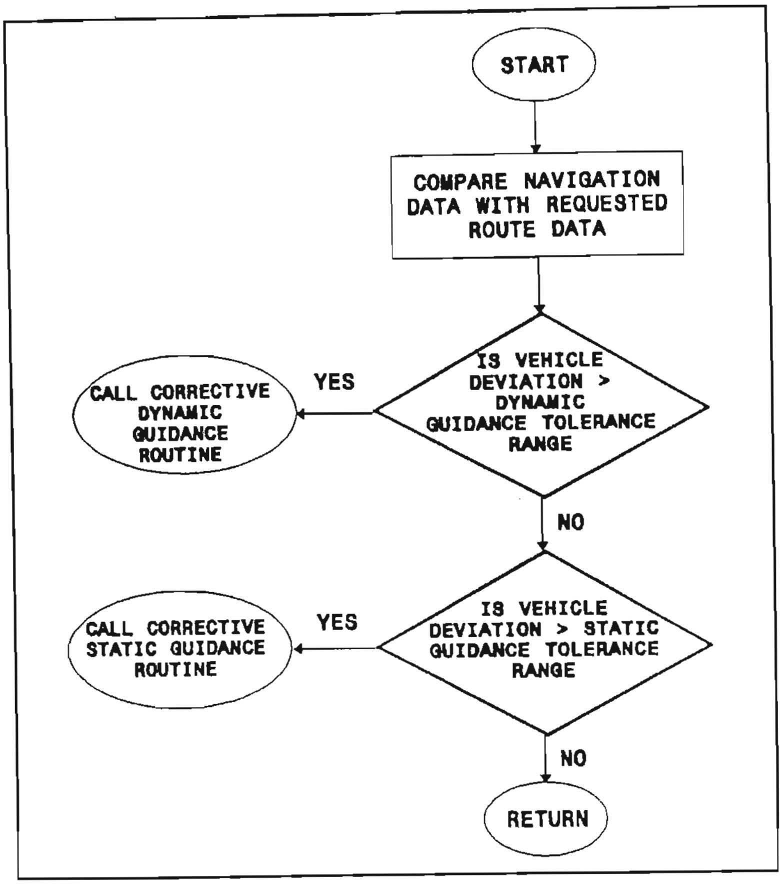


Figure 3-5: Subroutine Interfacing Navigation and Guidance

3.7.2 Subroutine and Algorithm for Corrective Dynamic Guidance.

The CAP transmits an end location via radio link to the AGV. The AGV then determines the correct route segments to follow in order to arrive at the end location. The route segment closest to the AGV is then passed to the main guidance subroutine. Navigational co-ordinates are received via radio link and are compared with the route segment. The subroutine activates the wheels to move in a forward direction along a vector. This vector is defined by a straight line between the AGV and the end of the path segment. The guidance subroutine continuously monitors the difference between the desired path location and the assumed real vehicle position which is determined by navigation. When corrective action is required to relocate the vehicle back on track, an algorithm is used to calculate the new direction of the vehicle. Using the navigational data and the start and end points of each route vector, a corrective rotation angle is calculated. This angle calculation is displayed below.

$$\tan \alpha_1 = \frac{Y_n - Y_s}{X_n - X_s} \cdot \dots \dots \dots \quad \text{Eqn 1}$$

$$\tan \alpha_1 = \frac{Y_e - Y_n}{X_e - X_n} \cdot \dots \dots \dots \quad \text{Eqn 2}$$

Where: X_n, Y_n are the navigational co-ordinates.
X_s, Y_s are the vector starting points.
X_e, Y_e are the vector ending points.

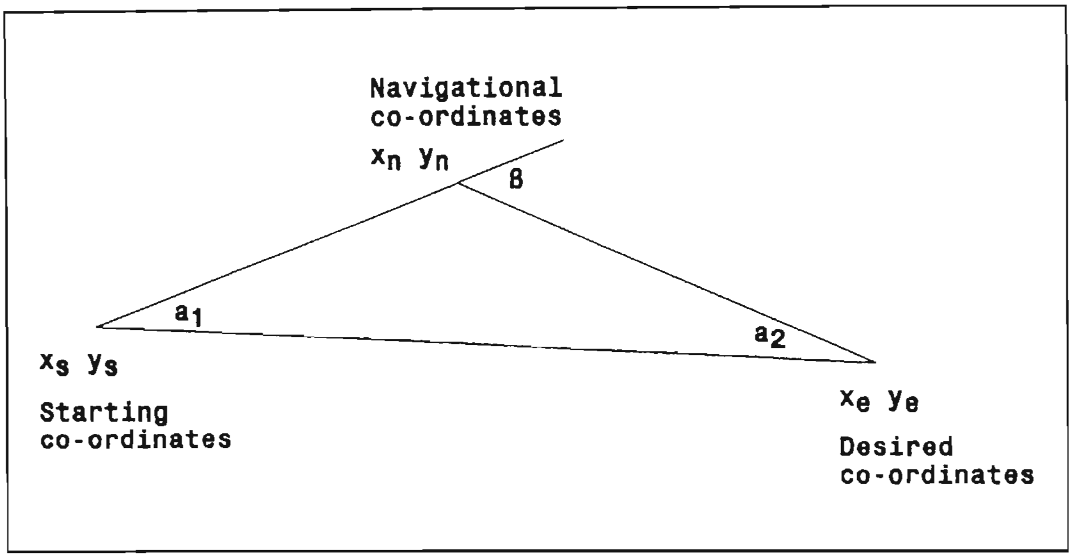


Figure 3-6: Angular Determination for Corrective Dynamic Guidance

Referring to the diagram and equations 1 and 2 above, it can be seen that beta (ß) is the required rotation angle to redirect the vehicle to its planned location. The angle beta (ß) is equal to alpha 1 (α_1) plus alpha 2 (α_2) ($\beta = \alpha_1 + \alpha_2$).

This is derived from the geometric theorem that an exterior angle of a triangle equals the sum of the interior opposite angles. A subroutine is called whenever a correctional guidance procedure is required. The angle ß is calculated using the assumed navigational co-ordinates (X_n, Y_n) and the starting (X_s, Y_s) and ending (X_e, Y_e) co-ordinates of the route segment. Negligible inertial effects arose when attempting to halt or rotate the vehicle because it was moving slowly (0.03 metres per second) during navigation and it had suspension on each wheel. A flowchart illustrating this dynamic guidance procedure is presented below.

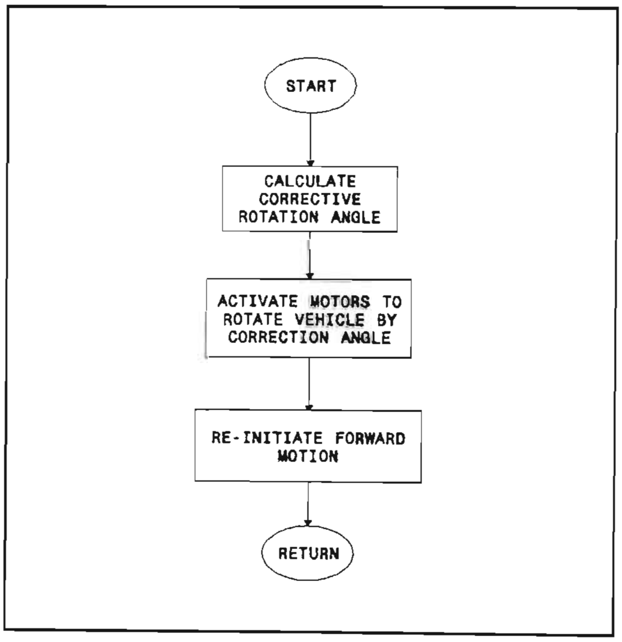


Figure 3-7: Subroutine for Corrective Dynamic Guidance

3.7.3 Subroutine and Algorithm for Corrective Static Guidance.

A separate algorithm is required for static positioning of an AGV. Whenever the navigation location point falls inside the area defined by the end location point, static navigation is implemented. When positioning the vehicle on a desired location, the vehicle platform should remain in the predefined direction. Assuming a vehicle had overshot a required location, it would be cumbersome and time consuming to rotate the vehicle before attempting to locate it. Therefore, under static guidance conditions, the vehicle maintains its pre-described direction and, using the Mecanum wheels, it alters its location by side, forward or reverse movements. A diagrammatic representation of this is presented below.

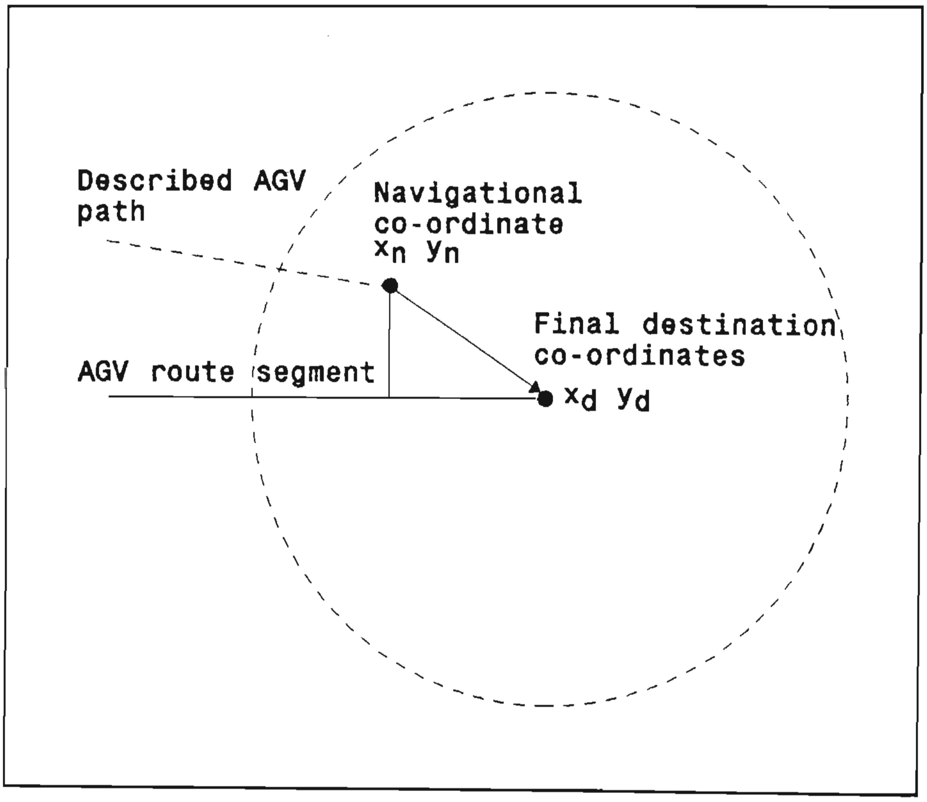


Figure 3-8: Diagrammatic Representation of Corrective Static Guidance

Referring to the diagram above, the static navigation is effected in the following manner. Upon the AGV entering the static guidance tolerance range a signal is directed to the guidance to halt the vehicle. A navigational co-ordinate position is recorded and then the X and Y displacements between the navigational co-ordinate and the desired end location are calculated. The vehicle traverses the calculated distance in a sideways direction. This realigns the vehicle on the route segment. The vehicle then moves the calculated distance in a forward direction to its final position on the desired end location. The subroutine for this procedure is presented below.

Many complex guidance algorithms have been developed which follow memorized paths (Arkin et al., 1990). Many are specific to the type of vehicle movement and the form of mapping required. An algorithm specifically suited for the Mecanum wheels has been developed by Dillman & Rembold (1988). It is felt that the application of these principles is beyond the scope of this development and seemed unnecessary in this application. This provides the framework for the application in this research of an original optical triangulation navigation technique.

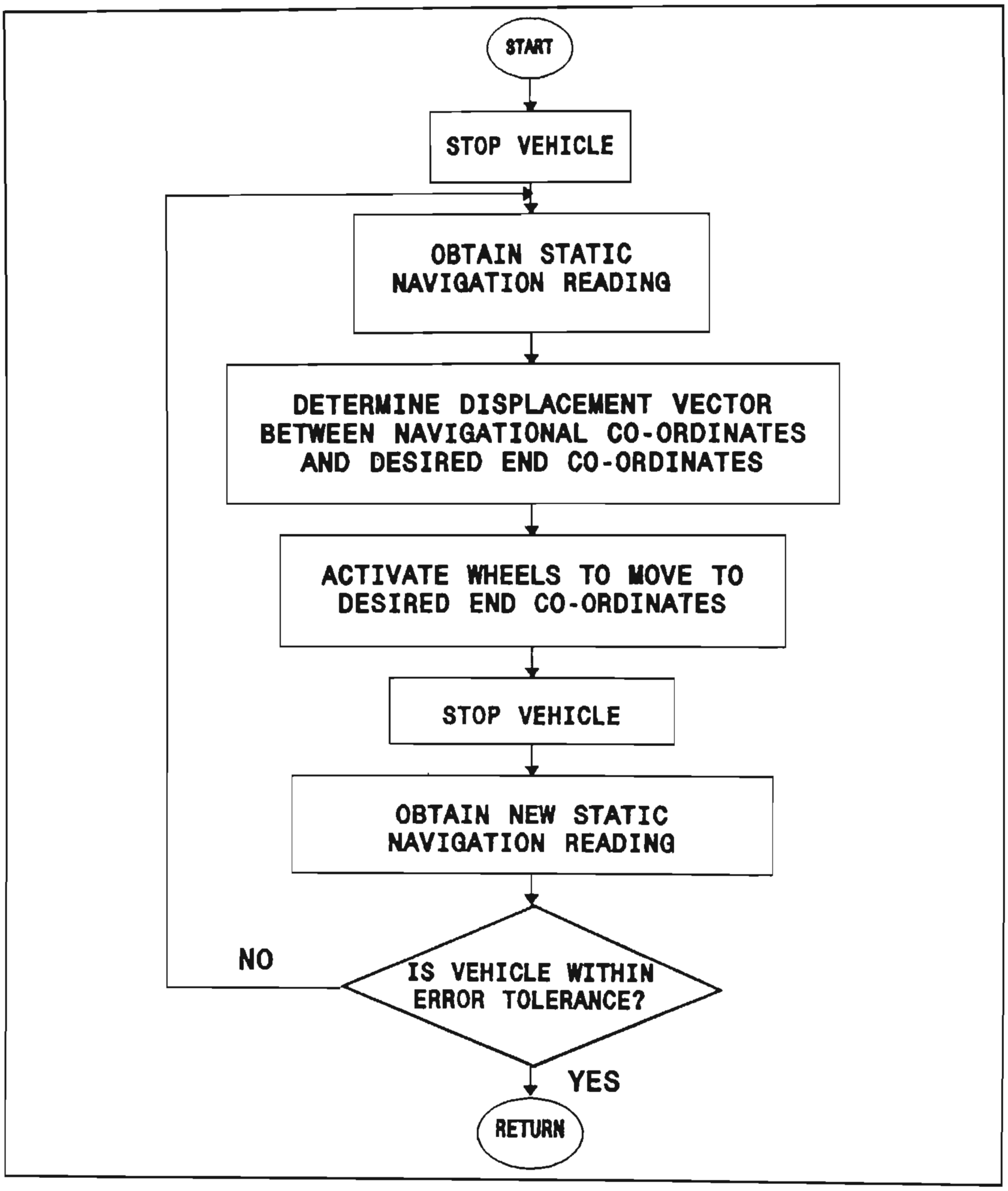


Figure 3-9: Subroutine for Static Guidance

CHAPTER FOUR
NAVIGATION

4.1 Introduction

The main objectives in researching navigation were to achieve low cost, ease of installation, flexibility, long range and high accuracy. It was considered that ultrasonic imaging used as a navigational technique posed problems of high overhead on the computing time of the onboard microprocessor. A further drawback was environmental interference experienced in a manufacturing environment as well as problems concerning positional accuracy (Arkin et al., 1990). Optical stereoscopic vision is costly to implement. Furthermore, the image processing consumes excessive computing time of the onboard microprocessor. Inertial navigational techniques are still in their infancy resulting in high costs, complex monitoring and inaccuracy. It is felt that optical triangulation offers good range, low cost, minimal interference, flexibility, accuracy and is comparatively easy to implement. Furthermore the use of infrared as an optical medium offered many advantages. Infrared light is a light beam which is not visible to the naked eye. It has the properties of a long wavelength when compared to the light spectrum and thus has difficulty penetrating the atmosphere. For this reason, it is useful in signal transmission and detection because only small quantities of this light wavelength occur naturally in the atmosphere. This enables the receivers to detect transmitted infrared light with limited interference. For these reasons, infrared optical triangulation was considered the most viable option for AGV navigation within a flexible manufacturing system.

4.2 The Concept of Triangulation

Triangulation is a method that has been developed to determine unknown positional co-ordinates. Triangulation techniques are easily understood in the field of surveying where unknown geographical points are determined using a theodolite. A further contemporary example is the global positioning system (GPS) (Bistrack Vehicle Positioning System, 1992). This uses satellites as beacons to triangulate its unknown position. Electromagnetic waves are used as the navigational medium and it is comparatively highly accurate when related to global positional determination. This system is inapplicable in a manufacturing environment because the physical ranges between the beacons and the receivers render accuracy to a minimum of 5 meters (Bistrack Vehicle Positioning System, 1992).

For clarity concerning the navigation system chosen in this research application it is necessary to understand the rudimentary concepts of triangulation. Three beacons are placed at three fixed known locations within an area and there is an unknown position, P. The location of P may then be determined by measuring the angular displacements ($\alpha 1$, $\alpha 2$ and $\alpha 3$) between the beacons with respect to the unknown position P. This concept of location determination is known as triangulation. The precision of this method is dependent primarily on the accuracy of measurement between the beacons from the point P. This then lays the basis for the choice of optical triangulation as a navigation technique. Optical triangulation was applied using infrared as a light source. This has comparatively little interference problems when concerned with transmitting and receiving if correct design procedures are adhered to. Therefore, it is advantageous in a harsh manufacturing environment where a large number of external interference factors influence most other navigation systems. Further reasons influencing the choice of this system were low hardware costs and ease of installation. If accuracy can be achieved this optical triangulation technique would offer distinct free-ranging navigational advantages.

4.2.1 The Multi-beacon Concept

For triangulation a minimum of three beacons are required for position determination. However, it was found that more than three beacons are advantageous in enhancing the flexibility of the navigation system and this is referred to as the multi-beacon concept. An example of a situation where more than three beacons are required arises when, in a three beacon environment, there is a temporary obstruction of one beacon. This would prevent the vehicle from determining its location. The obstruction could be due to a fixed physical object such as a machine or a moving object such as a vehicle or person. A further situation requiring a multi-beacon concept arises when a vehicle navigates in two separate areas. When the vehicle is operating in one area and the three beacons are only visible in the other the vehicle is unable to navigate. This can be overcome utilizing the multi-beacon concept to ensure that at least three beacons are visible at any one location within the two areas.

The concept of multi-beacon navigation requires that the navigation system identifies each beacon individually within the environment together with its predefined location. This information is required in the navigation algorithm when determining the vehicle position.

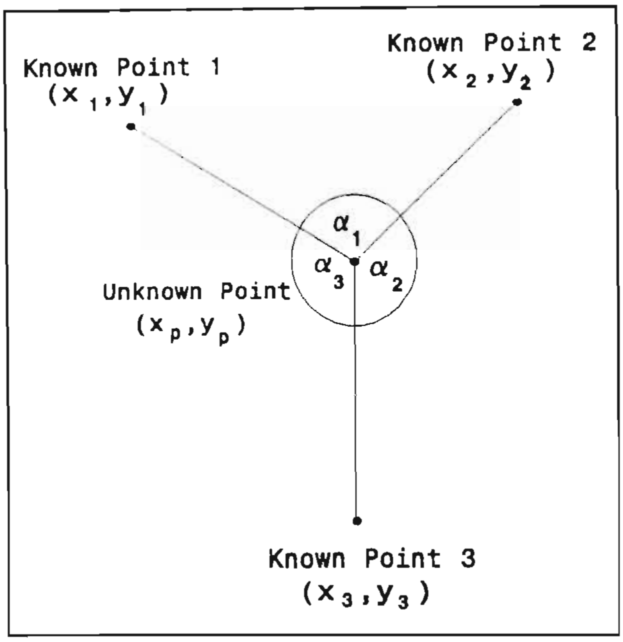


Figure 4-1: Diagrammatic Representation of Triangulation

Resection Formulae

$$A = \frac{Xbeacon2 - Xbeacon1}{\tan\alpha1} + Ybeacon2 - Ybeacon1 \ldots \quad \text{Eqn 3}$$

$$B = \frac{Ybeacon1 - Ybeacon2}{\tan\alpha1} + Xbeacon2 - Xbeacon1 \ldots \quad \text{Eqn 4}$$

$$C = \frac{Xbeacon3 - Xbeacon1}{\tan\beta1} + Ybeacon3 - Ybeacon1 \ldots \quad \text{Eqn 5}$$

$$D = \frac{Ybeacon1 - Ybeacon3}{\tan\beta1} + Xbeacon3 - Xbeacon1 \ldots \quad \text{Eqn 6}$$

$$X_p = -[Ybeacon1 + \frac{((C*B)-(A*D))}{(C-A)^2+(B-D)^2} * (B-D)] \ldots\ldots \quad \text{Eqn 7}$$

$$Y_p = -[Xbeacon1 + \frac{(C*B)-(A*D)}{(C-A)^2+(B-D)^2} * (C-A)] \ldots\ldots \quad \text{Eqn 8}$$

Figure 4-2: Algorithm for Position Recognition

Note:

Xbeacon1, Ybeacon1, Xbeacon2, Ybeacon2, Xbeacon3, Ybeacon3 are all co-ordinate positions of three beacons from a known reference point.

$\tan\alpha 1$ is the angular displacement between the first beacon and the second beacon measured from an unknown position with resultant co-ordinates X_p, Y_p.

$\tan\beta 1$ is the angular displacement between the first beacon and the third beacon measured from an unknown position with resultant co-ordinates X_p, Y_p.

X_p and Y_p are the resultant co-ordinate positions that are obtained from the resection formulae and define an unknown position P from the predefined reference point.

Many algorithms have been derived for position determination using triangulation, the most common being resection. The basic geometrical principle upon which the solution of the resection problem depends, is that all angles subtended by a chord in the same segment of a circle are equal (City Engineering Department, 1987). This is demonstrated in the circle theory (see Appendix III). Using this theory an algorithm was derived which was used here to calculate the positional co-ordinates of an AGV within its environment.

4.3 Navigation Systems

An initial system was designed employing the concept of a minimum of three stationary transmitter beacons of known location and one rotating receiver beacon of unknown location. This rotating receiver beacon could measure the angles between one fixed transmitter and the next. This system was designed to demonstrate the concept of triangulation with fixed transmitter beacons and the rotating receiver. From the outset it was understood that the use of conventional infrared receivers/decoders would limit it to static positional determination. Due to the slow response time of these components it could not determine the positional requirements of a moving AGV. In order to implement a navigational system that could operate effectively in a dynamic AGV environment a second system was developed. System two utilized the concept of one rotating transmitter beacon of unknown location and three stationary receiver beacons of known location. The implementation of system two proved to be successful for the requirements of this research application. On the basis of the experimental data and experience gained from this implementation it was possible to propose a third system. Details of this are presented in chapter six.

SYSTEM ONE	SYSTEM TWO
3 stationary transmitter beacons of know location.	3 stationary receiver beacons of known location.
1 rotating receiver of unknown location.	1 rotating transmitted beacon of unknown location.

Table 4-1: Table comparing System One and System Two.

4.4 System 1: Design Criteria

This concept implements triangulation by transmitting infrared light from fixed, known, stationary beacons. The conceptual design operates on a principle whereby a minimum of three transmitter beacons are placed at predefined co-ordinate locations within the AGV working environment. Each of these stationary beacons transmit pulsed light at an allocated unique transmitter frequency. The infrared transmitters should have at least a 50° spectral angle to allow for acceptable transmitted light coverage over the AGV working area. It should be noted that navigation can only occur in the area where all three infrared beams coincide. A narrower spectral angle would greatly reduce the working area of the vehicle. An infrared receiver is placed onboard the AGV in an enclosed housing with a rectangular slit. This eliminates the viewing of light on the horizontal plane except when the receiver is facing directly towards a given infrared transmitter beacon. Light can still be viewed on the vertical plane. This permits the transmitter beacons to be placed at variable heights within the working area.

The infrared receiver rotates with the aid of a stepper motor which maintains precise incremental rotational position. The exact angular displacement of the rotating housing can be determined by continuously logging the number of output pulses passing from the computer to the stepper motor driver circuitry. In this manner precise angular measurements between transmitter beacons may be determined. This process is effected using an incremental counter which is in the main program of the microprocessor onboard the AGV. The housing is rotated firstly 360° in a clockwise direction; this process is then reversed as it rotates 360° in an anti-clockwise direction. This procedure is continuous. In such a manner the wires that are connected into the housing are prevented from becoming excessively twisted.

Provided stepper motors are correctly driven and controlled, the problem of pulse skipping should never occur as is verified by the control achieved in stepper motor drivers utilized in plotting applications. However, presuming this unlikely incident occurs, the positional data would be discarded by the microprocessor as it would result in an out-of-range co-ordinate.

Once the infrared signals have been received their frequencies are decoded, resulting in separate output signals corresponding to each received input frequency. Each of these signals are allocated a unique microprocessor input port. External decoder circuitry deciphers the received frequency and thus determines which beacon the receiver is facing and informs the microprocessor. On line navigational positional data can be calculated by measuring the angular displacement between three beacons with respect to an AGV. This is calculated using an algorithm derived from the triangulation theory. Once the navigational position has been determined these values are implemented in the guidance and sent to the landbase for position recognition and visual near real-time display.

For an AGV to navigate effectively a multi-beacon environment should be implemented. This would prevent potential obstructions such as equipment or personnel from influencing the navigation. Obstructions that block the light from reaching the receiver interfere with the system's ability to implement the proposed computational method for position definition.

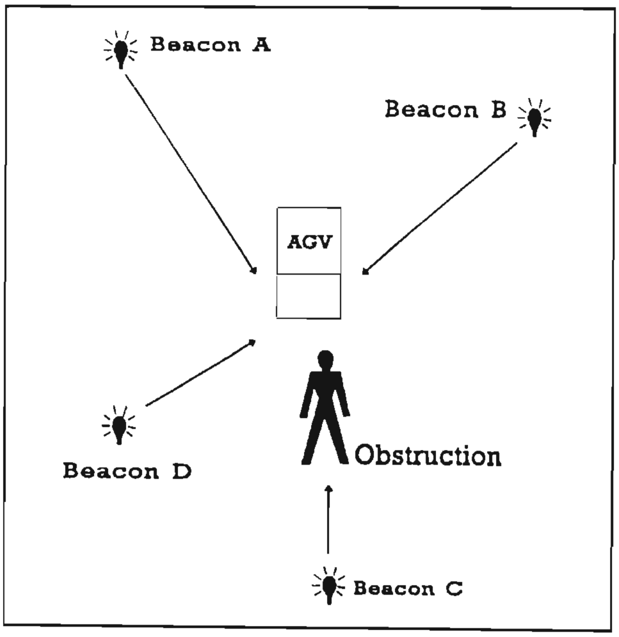


Figure 4-3: Diagrammatic Representation of Navigational System

4.5 Hardware Design and Construction

Prior to any navigational hardware construction it was necessary to design and test the infrared transmitter and receiver circuitry. This is because variables such as range, interference, transmitter mark space ratio, response time and transmitter drive current had to be established. Once the design proved to be viable for the intended application, the onboard AGV navigational apparatus including the stepper motor driver circuitry, frequency decoder circuitry and motherboard interface was then designed and implemented.

4.5.1 Infrared Signal Encoding and Transmission

A high power infrared transmitter (Part Number: TSUS 5402, Spectratech, 1992) was chosen for the transmitter beacon light source. A spectrally matched infrared receiver (Part Number: IS 471F, Spectratech, 1992) was selected for the infrared receiver beacon. This selection allowed for the receiver to react only when energized with the correct wavelength of light. Of note, is the wavelength of transmitted and received light falls into a narrow band ranging from 980-1020 nanometres which inhibits other wavelengths of light from interfering with the receiver. To reduce interference even further the receiver module only accepts incoming light when the light beam is pulsed at a frequency of 38 kHz. A 5 kHz bandwidth is permitted for variances such as temperature drift. When the infrared receiver accepts incoming light at the correct wavelength of 1000 nanometres pulsed at 38 kHz it produces a 5 volt steady state output.

For beacon identification, a unique lower frequency was modulated onto the 38 kHz excitation frequency. This resulted in each beacon transmitting spectrally matched light with a base frequency of 38 kHz and a unique lower frequency. The unique frequencies chosen for this application and which identify each beacon individually were determined from calculation. These values were constrained by factors influencing the receiver module and decoder circuitry (see

Appendix II). The resultant values were 600 Hz, 500 Hz and 420 Hz. The 38 kHz astable timer output had a 10 percent duty cycle. This output sourced the gate of a mosfet which in turn switched an infrared transmitter diode. The effect being that the infrared transmitter was energised for only 10 percent of the time. This was configured to comply with the constraints specified for the emitter diode. Although a maximum of 100 milliampere average current is allowed to pass through the diode, a repetitive peak current of 3 amperes maximum can be endured for short durations of this pulsing time. Working within these boundaries the circuitry energised the emitter diode for 10 percent of the duty cycle. During this 10 percent duty cycle, 1 ampere flowed through the diode which resulted in an average diode current of 100 milliamperes. To achieve this high current pulse, the output from the timer sourced the gate of a P type mosfet (IRF520) and this energised the LED through a limiting resistor, resulting in 1 ampere on current. This high current enabled the infrared LED to transmit a more intense pulse of light which improved the permissable transmission distance between transmitter and receiver. To achieve this pulsing configuration two 555 timers were utilized (National Semiconductor Corporation, 1988). The one operates in an astable mode with the output oscillating at 38 kHz. A separate timer with a unique frequency associated with each beacon was connected to the reset of the 38 kHz astable timer (see figure 4-5). This compounded output sourced the gate of a mosfet which in turn supplied the infrared LED with a current of 1 ampere. The resultant emitted light waveforms can be seen in Figure 4-4.

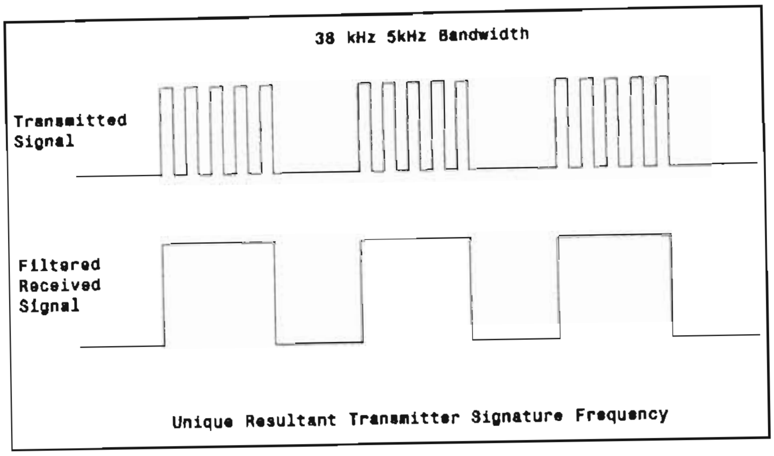


Figure 4-4: Diagram of Compound Output Waveform

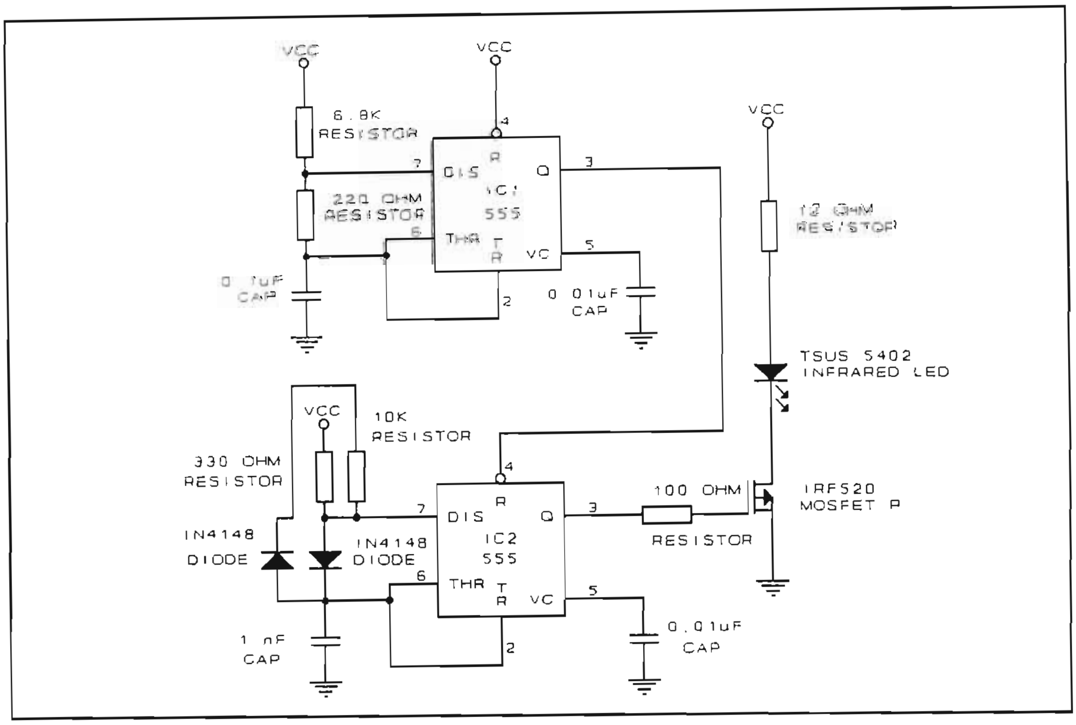


Figure 4-5: Schematic Diagram of Infrared Transmitter Circuitry

4.5.2 Infrared Signal Reception and Decoding

An infrared receiver and filter packaged complete with integrated circuitry (Part Number: IS 471F, Spectratech, 1992) was used as the receiver module. This module is supplied with a focusing lens. The package incorporates full processing circuitry. The specification states that the photo-transistor contained within the receiver module was to be excited with incoming light that specifically comprised a 1000 nanometres wavelength. The infrared photo-transistor signals are filtered internally with a band pass filter. This filter is configured with a centre frequency of 38 kHz and a 5 kHz bandwidth. Incoming light signals with frequencies ranging from 36 kHz to 41 kHz produce a resultant output logic signal (Spectratech, 1992). A maximum decoding time of 800 microseconds is specified. This decoding time is the most influencing factor concerning navigational accuracy and positional data accumulation rate. This value determines the maximum unique beacon frequencies permitted. From this the minimum overall unique beacon frequency decoding time may be calculated (see Appendix II).

Whenever, the infrared receiver module faces an infrared emitter beacon it is energised by the emitted compound light waveform. The receiver module filters the superimposed carrier frequency component from the composite light waveform. This results in filtered receiver module output signals comprising solely of the unique lower beacon frequency component. The signal conditioning within the infrared receiving module is completed. Each transmitter beacon has a separate associated decoder onboard the vehicle. National LM567 decoders were selected and each configured to demodulate a unique beacon frequency. A bandwidth for each unique excitation frequency was chosen. The bandwidth span adopted was 10 percent of the excitation frequency. The specification of the LM567 allocated a maximum number of cycles for the decoder to lock onto its pre-configured frequency (National Semiconductor Corporation, 1988). For a 10 percent bandwidth a maximum of 15 cycles is specified. When an input frequency signal matched any of the pre-configured decoder trapping frequencies, the resultant associated decoder output changed from 5 volts to 0 volts.

The decoder outputs were connected to interrupt ports of the microprocessor which in turn selected navigational subroutines to be executed (see system software). The calculations in Appendix II indicate that the time taken to identify each beacon influences the resultant angular resolution and the rotational speed of the beacon. This is detailed in the discussion of the proposed third navigational system in chapter six.

4.6 Onboard Navigational Hardware

The onboard mechanical hardware consists of a stepper motor, a rotating housing which contains the infrared receiver as well as gearing. The rotating housing is mounted on the highest platform of the vehicle in order to avoid beacon obstruction. This is located at the front of the vehicle on the upper lid of the enclosure containing all the microprocessor and associated electronics. A stepper motor is placed on the underside of the upper lid of the enclosure. The rotating housing is connected through the upper lid via a shaft onto a tooth gear. This gear is connected to the stepper motor using a tooth belt. The rotating housing contains the receiver module. Emitted signals are only received into the module when the module is facing directly towards the beacon. This is achieved using two parallel plates 300 millimetres long, 4 millimetres in width and painted mat-black to avoid reflective light readings. The parallel plates are connected vertically onto the rotating housing. The housing is sealed from all light interference except from that entering the vertical slit. This restricts light rays on the horizontal plane, but it is insensitive to light in the vertical direction. This allowed for a variation in the vertical height placing of the transmitter beacons. A diagram indicating the design of the rotating receiver is presented below.

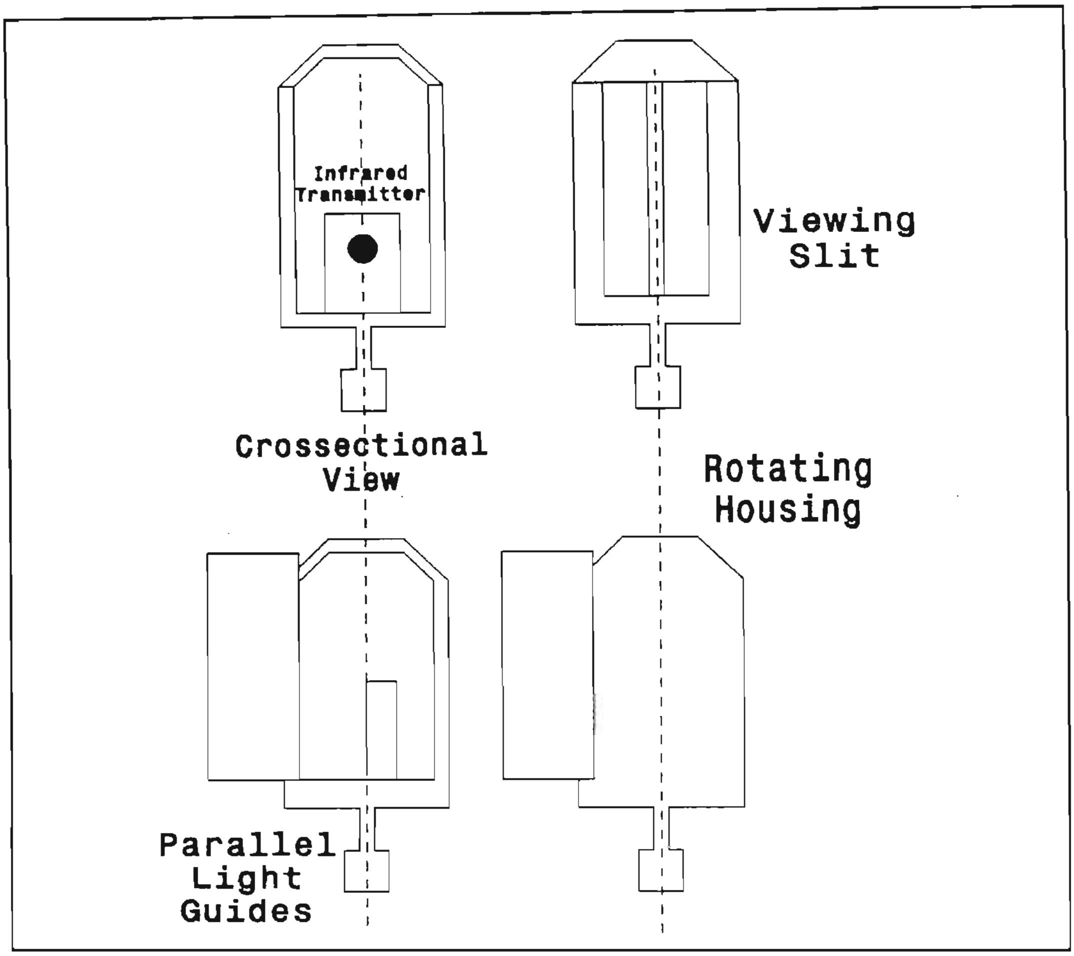
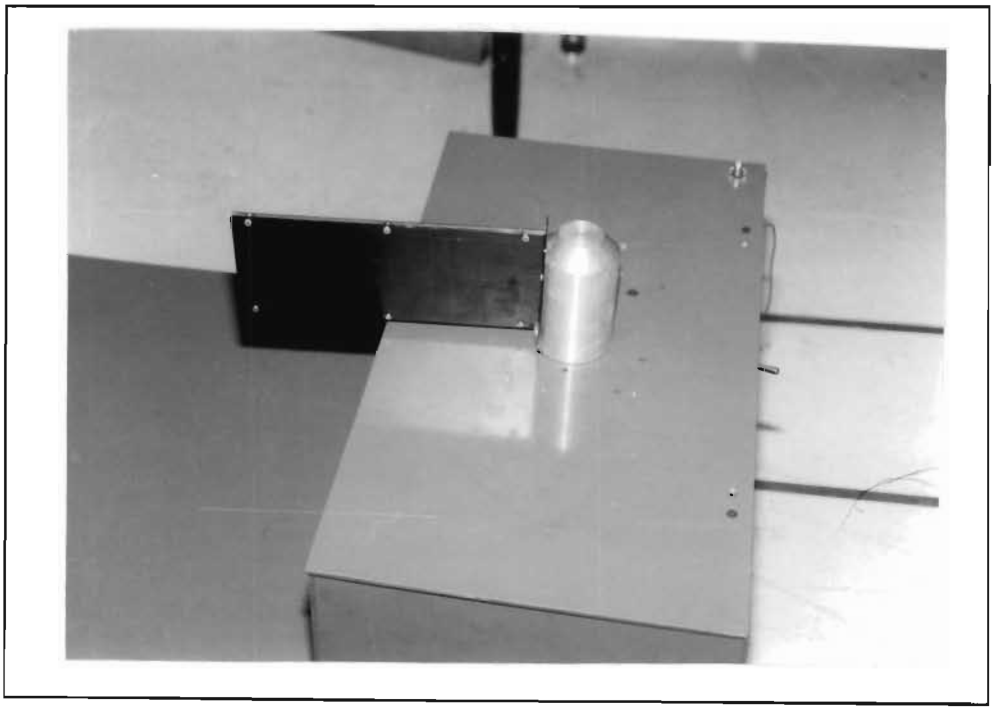


Figure 4-6: Diagram of Rotating Beacon.



Photograph 4-1: Photograph of Rotating Beacon

The housing is constructed of aluminium to reduce the inertia problems which occur with slow moving stepper motors. The inertial effects are exaggerated further due to the backlash when the direction of rotation is changed. Although inertia does not cause the motor to miss a step, it does result in a vibration of the receiver housing and consequently, inaccuracies in the measured angle.

Three wires are fed through the centre of the driver shaft of the rotating housing. Two of these wires are used to power the receiver, namely +5 Volts and 0 volts. The third wire supplies the received signals to the decoder board.

4.6.1 Stepper Motor Circuitry

Four output ports drive the stepper motor directly through transistors in a unipolar fashion. The system is initialised by an optocoupler which is interrupted by a metal tag mounted on the rotating housing. The signal from this optocoupler is supplied to a microprocessor port. The system is initialised by slowly rotating the housing with the aid of the stepper motor until the optocoupler is interrupted. This interruption occurs when the rotating housing is facing directly to the front of the vehicle. Once initialised, the stepper motor rotates the housing 360° in a clockwise/anticlockwise direction, preventing excessive twisting of the connecting wiring. The 0.5 ampere, 200 pulse/rev stepper motor is driven from 12 Volts through a 4.7Ω limiting series resistor and four darlington transistors in a unipolar configuration. It is considered that a more complex stepper motor driving circuitry system is unnecessary for this relatively simple application. Each of the four motor poles are driven by separate 8255 output ports from the microprocessor. These output port signal lines are internally current limited to 20 milliampere and are connected directly into the base of each transistor. TIP 120 transistors were selected to drive the stepper motors. These transistors have a specified current gain of 1000 resulting in a maximum saturation current of two amperes. This adequately covered the stepper motor current requirements which were 0.5 ampere driving current (current limitations were set by the 4.7Ω limiting resistor).

The stepper motor coil resistance was measured to be 5Ω and the series impedance resistor of 4.7Ω was selected. This resulted in a steady impedance of 9.7Ω. The resultant maximum steady state current was 12/9.7 = 1.24 ampere. These calculations are based on Ohm's Law:

$$\text{ohms} = \text{volts} / \text{amperes} \quad . \; . \; . \; . \; . \qquad \text{Eqn 9}$$

It should be noted that this current cannot be realised as the motor is constantly in motion, the effect being that the resultant impedance of the system is consistently far greater than 9.7Ω. Flyback diodes are connected across each motor coil winding to ensure transistor over-voltage protection. This is clarified in the schematic diagram of the stepper motor driver-circuitry configuration.

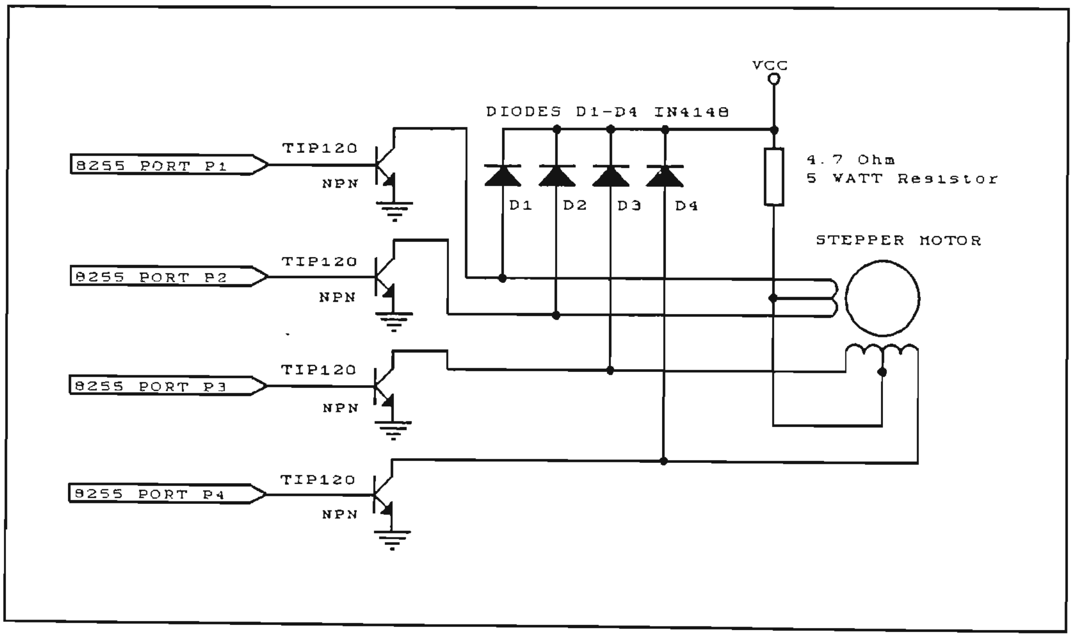
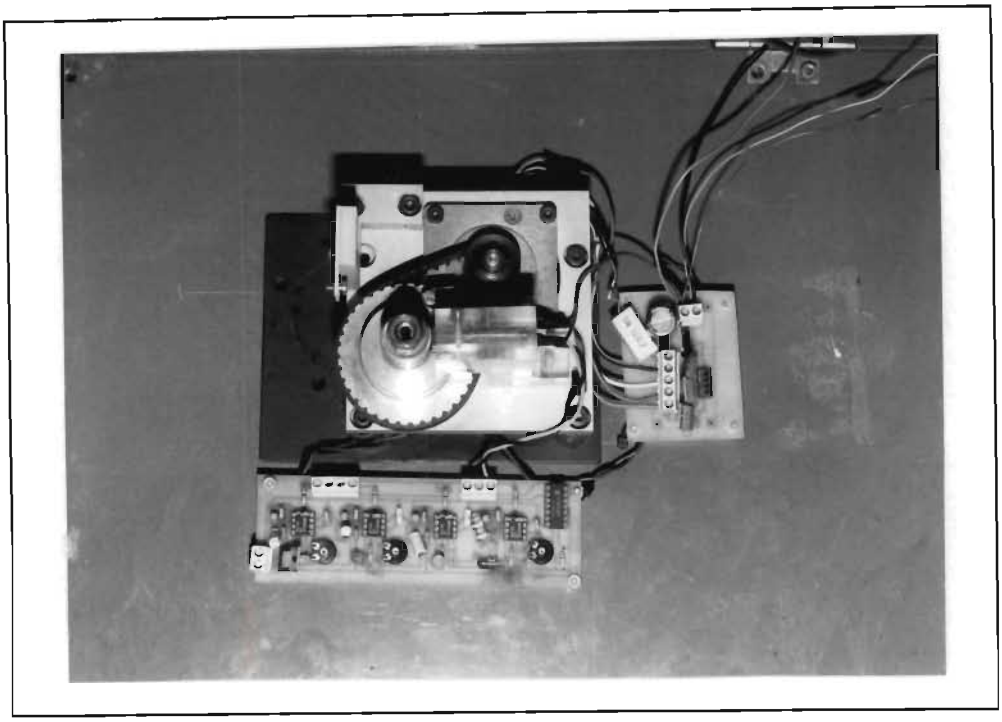


Figure 4-7: Schematic Diagram of Stepper Motor Driver-Circuitry



Photograph 4-2: Photograph of Stepper Motor and Decoder circuitry

4.7 System Software

Two hundred pulses are required for one stepper motor revolution. The tooth belt gear ratio chosen is 3.6:1 and this results in a 720 pulse/revolution configuration or 1 pulse/0.5°. The program produces sequenced pulses to four output ports which consecutively drive the stepper motor windings. For each stepper motor output pulse, the program increments an internal counter. The ports are set high in a repetitive sequenced fashion. Each pulse increments the motor one step. In this manner the counter monitors the angular direction of the rotating housing. An accuracy of 0.5° is determined by the value of the counter because each pulse is equivalent to 0.5°. When the counter reaches the value 720, this indicates that one full revolution has occurred. At this stage, the pulsing sequence is reversed. This changes the direction of the stepper motor and rotating housing respectively. The counter value is then reduced in value until the value zero is reached. The process is then restarted. Most of the program time is consumed by this driving sequence. This has proved to be problematic as the remaining processing time is limited and the program cannot perform all the other necessary functions.

To identify each beacon individually a separate interrupt is connected to each LM567 decoder. Each of these decoders are configured to identify their associated beacon pulse frequency. The INTEL 8088 microprocessor is able to distinguish which decoder has been activated through its ability to differentiate between the different interrupt signals. The separate interrupt inputs have distinct subroutines. Each interrupt is associated with an individual decoder and subroutine. This association permits each transmitting beacon to be linked with its predefined subroutine which contains data of the specific beacon's co-ordinate location. When the rotating receiver beacon faces a transmitting beacon the corresponding decoder interrupts the program. The associated subroutine then records the value of the incremental counter. This value, together with its affiliated beacon, is stored. Once values for three individual beacons have been stored, a subroutine is executed to calculate the AGV's positional co-ordinates. This calculated position is utilized in the guidance algorithms. Furthermore, the data is output through the RS-232C communications port and transferred using the modem-radio to the landbase.

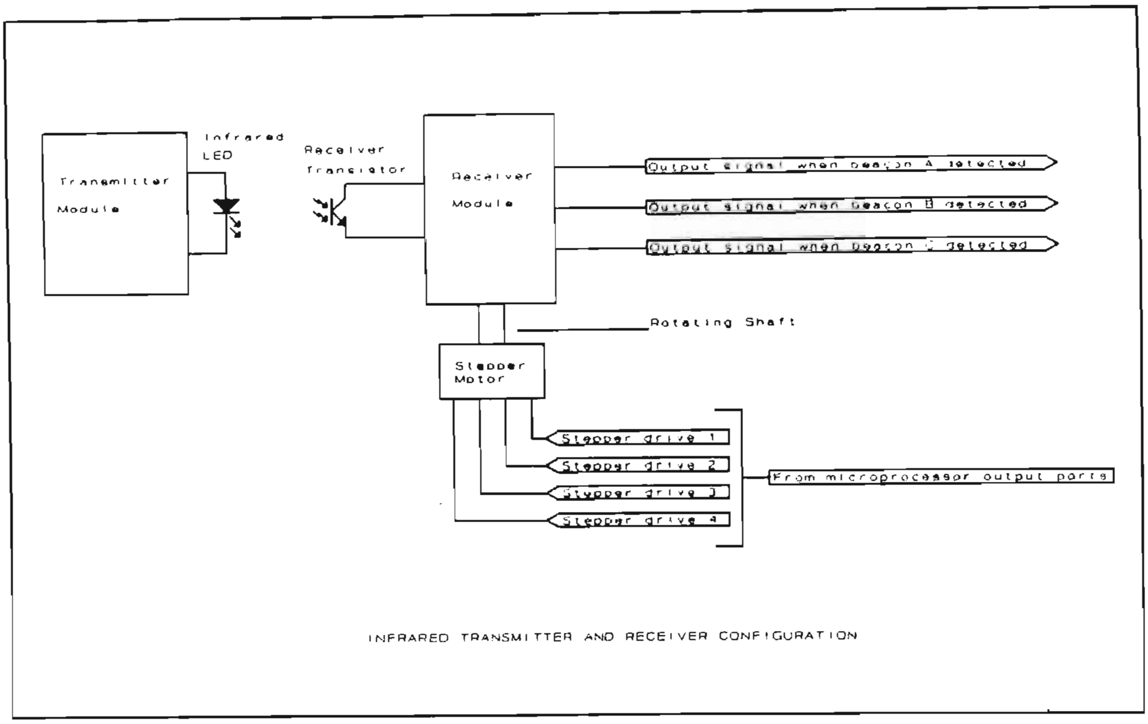


Figure 4-8: Block Diagram of Signal Flow for the Navigational System

4.8 System Performance

System accuracy is defined as the difference between the real location and the navigational measured position of the AGV. When determining static accuracy there are two variables to consider. The first is the precision of the measured angular displacement. This incorporates factors such as angular resolution, time taken for the controlling microprocessor to react to a beacon identification interrupt and the mechanical inaccuracies of the system. The second incorporates the position of the vehicle with reference to the beacons and placement of the beacons within the working environment. To determine a moving vehicle's dynamic navigational accuracy a further two interrelated factors must be considered. These are the vehicle .speed which can be linear or rotational movement and the speed of the angular rotating beacon. If the navigational system is constrained to a slow rotational beacon then a correspondingly slow vehicle speed is required.

Similarly, a fast vehicle speed requires a corresponding fast rotating beacon. The overall navigation performance can be measured by a combination of these aforementioned variables.

4.8.1 Static Accuracy

The angular resolution of the system is defined as the smallest angular displacement that may be recorded. To analyze static accuracy of a working environment a mathematical experimental model was constructed in the following manner. Three beacons were placed equidistantly apart in a 4 metre square working environment. An AGV was placed at the epicentre of the three beacons. The stepper motor had a resultant angular resolution of 0.5°. Given these conditions the best possible resolution that can be attained is 23 millimetres in the X-direction and 46 millimetres in the Y-direction. The calculations for a 0.5° tolerance range is detailed in Appendix II. This representation is given in the diagram below.

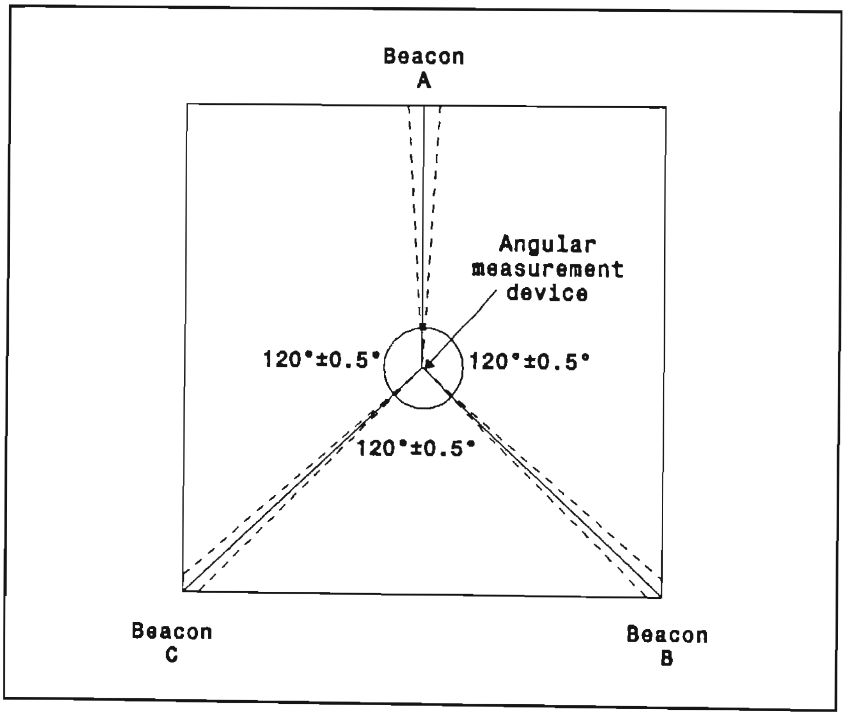


Figure 4-9: Diagram representing AGV Navigational Accuracy Tolerances.

Although this model depicts an acceptable linear variation there are two other physical variances which influence the triangulation calculations resulting in greater tolerance. These are the position of the AGV with reference to the working zone and the position of the beacons relative to each other. The accuracy of the navigation system decreases when a vehicle approaches the direct line between two beacons. This is because the measured angle between the two beacons with reference to the vehicle approaches 180° as demonstrated below.

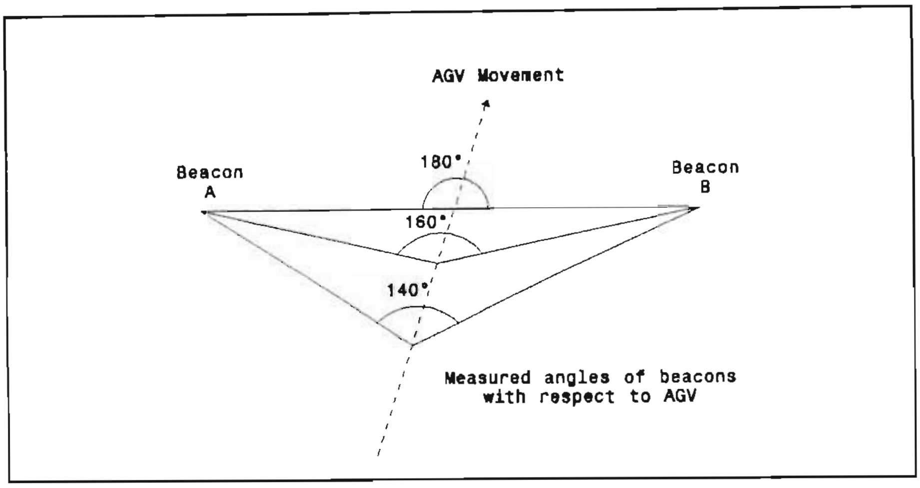


Figure 4-10: Representation of Measured Angles of Two Beacons With Respect to AGV as it Passes Through 180°

Inspection of the resection algorithm reveals that the value of TAN α is required for positional determination, where alpha is the measured angle between the two beacons. The value of TAN α as alpha approaches 180°, tends to zero. Investigating the resection formula reveals that the values of TAN α are used in the denominator of the equation. As the denominator approaches zero the resultant value of the equation approaches infinity. Due to the nature of computer floating point arithmetic procedures, large numbers are truncated leading to inaccuracies. Likewise, if the measured angle between two beacons in relation to the vehicle approaches 0° then the same computational problems arise. Based on these considerations an ideal beacon placement and the resultant AGV working zone is demonstrated.

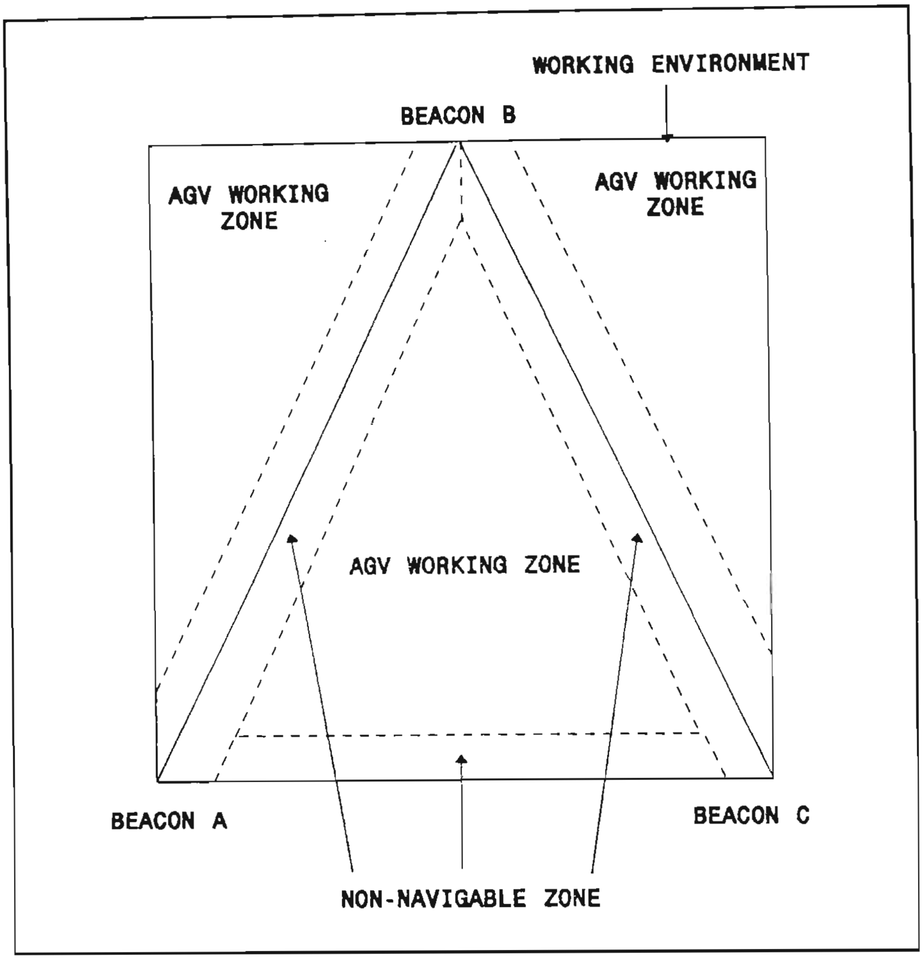


Figure 4-11: Diagrammatic Representation of AGV in a Three Beacon Working Environment

It is sometimes required that an area outside the three beacon triangle is needed for a navigation zone. If the working environment is not large enough to expand the placement of the beacons then the navigational zone is restricted. Under these circumstances, the implementation of a four beacon system could be considered. Extra programming would discard a beacon as the measured angle between two beacons with reference to the AGV approaches

180°. Given these conditions the program would utilise the fourth beacon as required.

In the four beacon environment displayed below the non-navigable area occurs where the AGV falls in a direct line between beacon A and B and at the same time falls in a direct line between beacons C and D.

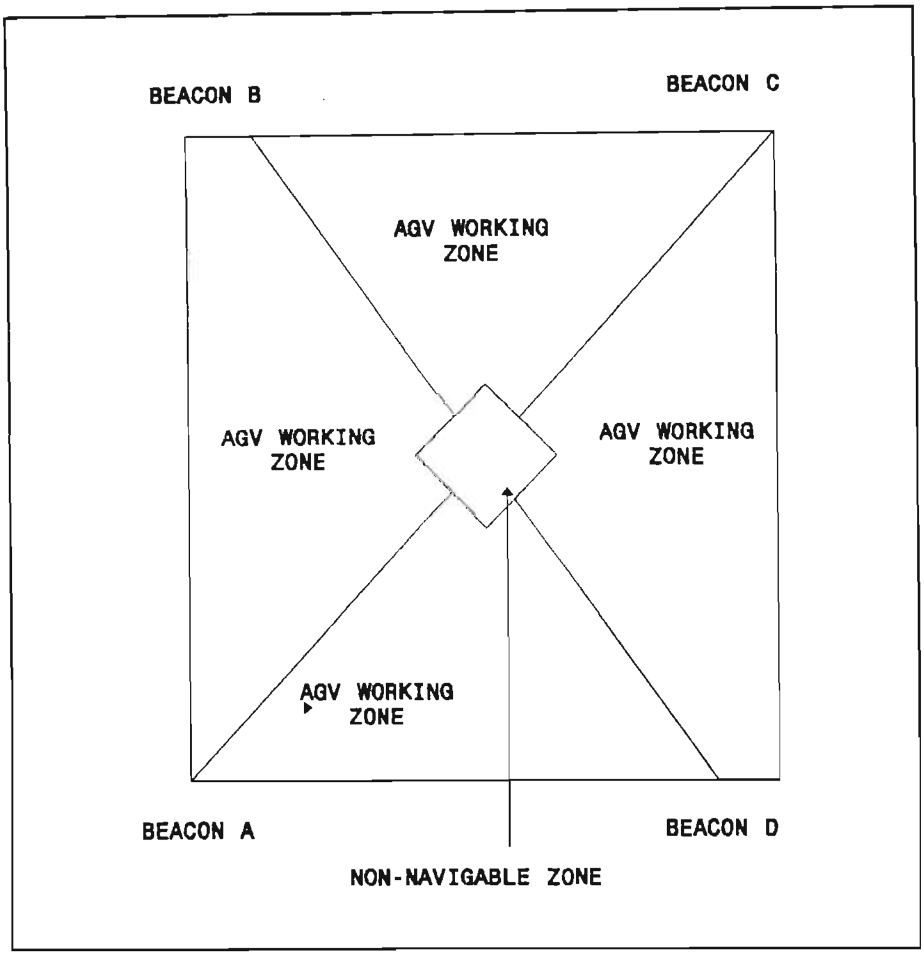


Figure 4-12: Diagrammatic Representation of AGV in a Four Beacon Environment

In a working environment it is possible that at any one time a beacon may be obstructed from direct line of view of the AGV. These obstructions could be due to a machine, other AGVs or people. This situation gives rise to a further need for a multi-beacon system to be implemented.

4.8.2 Dynamic Navigational Accuracy

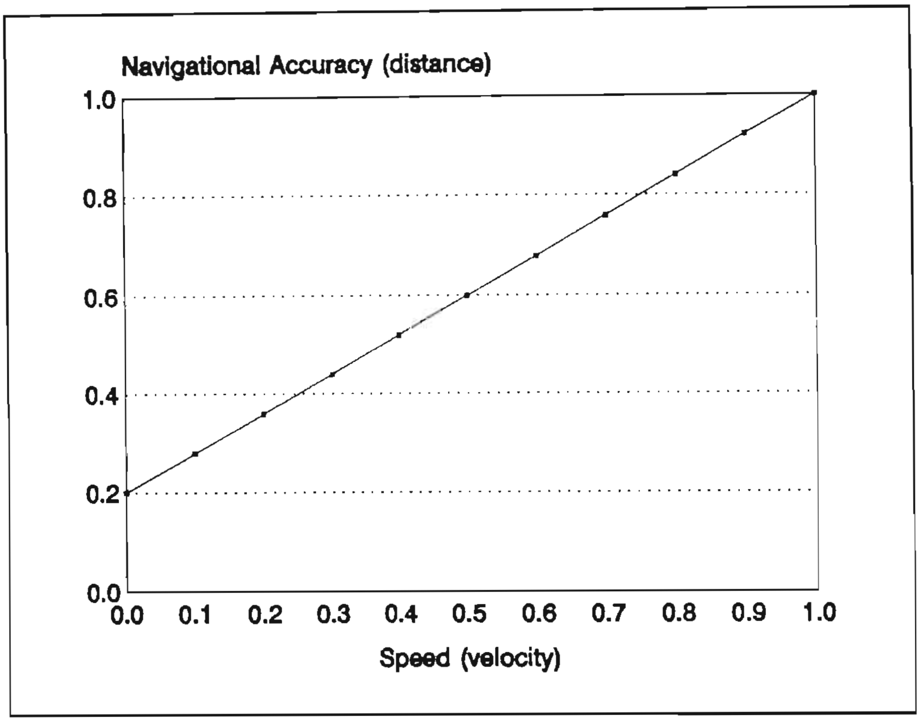
Contrary to static navigational performance when considering dynamic navigational performance, the vehicle speed and time of beacon rotation must be taken into account. If a vehicle is stationary, then the time for the navigational apparatus to accumulate the angular displacements between the beacons does not have to be taken into account. Alternatively, when a vehicle is moving, the indeterminate navigational position and the angular displacements between beacons are continually fluctuating. This suggests that the longer it takes to accumulate the three angular displacements between beacons, or the faster the vehicle is moving, then the greater the resultant navigational inaccuracies will be. As discussed above it is clear that the two variables are directly associated to the dynamic accuracy for the navigation of an AGV. Therefore a formula was derived which can be directly applied to the dynamic accuracy of the system:

$$D\ A\ (m) = V\ S\ (m/sec) * T\ (secs) \cdots\cdots\cdots\cdots \text{Eqn } 10$$

Where: D A = Dynamic Accuracy,
V S = Vehicle Speed,
T = Time to accumulate data is measured in sec

This formula can only be considered as an estimate of dynamic accuracy. Other factors that could influence the navigational algorithm are variances in the dynamic measured angle. These variances arise when the vehicle attempts to accumulate navigational data while moving. During this motion the relative angular positions of the beacons change with respect to the vehicle. An analogy can be made between this and taking photographs of surroundings from a moving vehicle. When taking the photograph with a slow aperture the resultant picture will look blurred. The use of a fast aperture results in a more defined picture. This is as a result of the shutter speed being relative to the speed of the vehicle. This is analogous to the navigational system implemented in this research where the AGV speed is relative to elapsed time for positional data accumulation.

When determining overall navigational accuracy of a moving vehicle the dynamic and static accuracies should be added together. The dynamic navigational formula is implemented on the graph below. A theoretical graph depicting static and dynamic accuracy as a function of linear speed is displayed.



Graph 4-1: Representation of Navigational Accuracy as a Function of Linear Speed

4.8.3 Factors influencing Static Accuracy of System 1

Static trial tests were performed on the navigation system revealing considerable inaccuracies. These inaccuracies resulted mainly from the manner in which the hardware and software apparatus functioned jointly. The most significant errors revealed in the trial tests resulted from the slow response of the decoders as well as the delay time for the

INTEL 8088 microprocessor to react to an interrupt signal. As can be seen in Appendix II the resultant maximum decoding time was 35.7 milliseconds. The beacon rotated at 0.143 revolutions per second (1 revolution/7 seconds) and covered an angular displacement of 1° in 19.4 milliseconds. The measured time to service an interrupt request ranged from 3 to 65 milliseconds with an overall average of 40 milliseconds. The overall effect of using a beacon rotation speed of 1 revolution per 7 seconds resulted in an angular resolution of 4°. The maximum angular error reading of 4° was applied to the ideal model displayed below. Theoretical calculations presented in Appendix II indicate the tolerance limits expected when implementing a navigation system with these criteria. The results from this analysis indicate a linear resolution in the X-direction to be 193 millimetres and in the Y-direction to be 370 millimetres. It should be noted that this is merely an indication of the resolution attainable. Factors already mentioned, such as, position of the beacons, position of the AGV and beacon rotational speed all alter this end result. Below is a diagrammatic representation depicting the angular variances measured from the AGV with respect to each beacon.

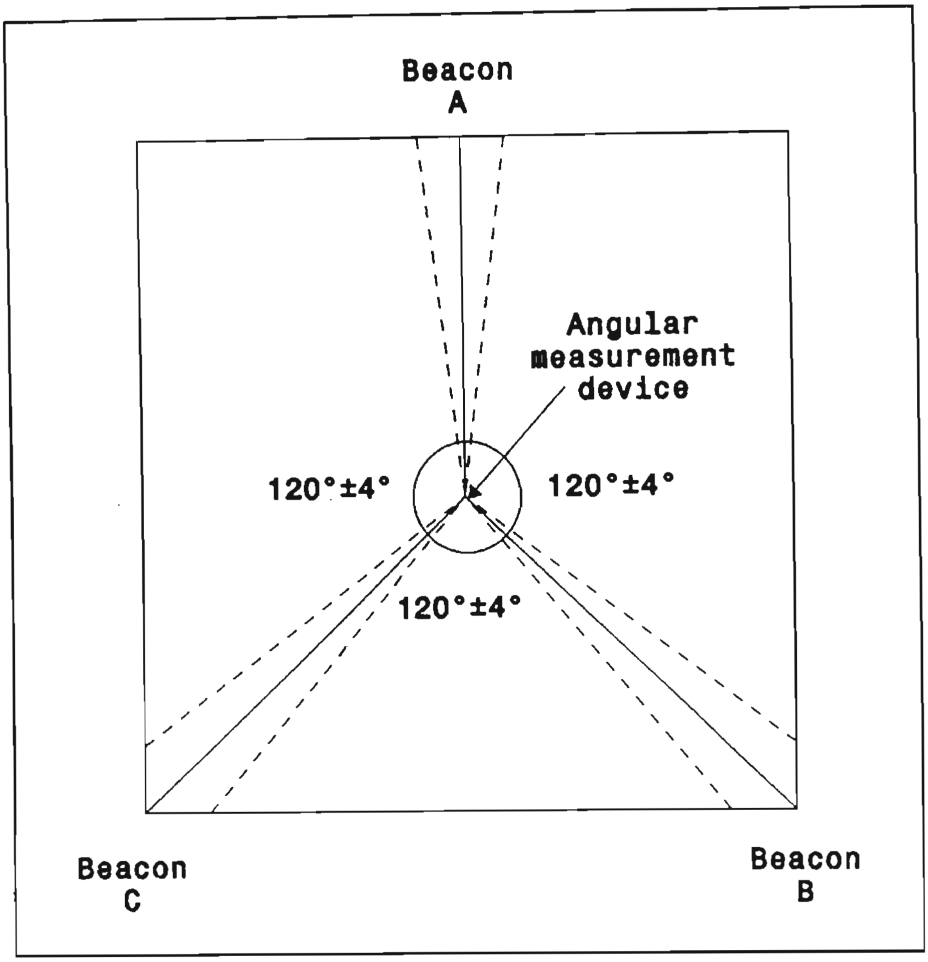


Figure 4-13: Diagram of the Angular Variances Measured from the AGV with respect to each Beacon.

This navigational solution was applied utilizing a relatively slow rotational beacon speed and resulted in poor static accuracy. As a result of these poor readings dynamic accuracy was not investigated. The navigational solution of this research is not to be limited to a laboratory application but is to be employed for use on AGVs within a larger manufacturing environment. In conclusion, these inaccuracies rendered this system inappropriate in its present form for application in a manufacturing environment. Therefore, it was necessary to investigate variations on this system.

Application of this navigational system revealed that optical triangulation could result in a viable navigation system for free-ranging AGVs within the manufacturing environment. From this basis a second navigational system was developed. The main objectives defined here were to implement a system which would have a rapid data accumulation rate (1 second) while still maintaining acceptable accuracy tolerance limits (angular resolution of 0.5°).

System two which is proposed in this research application required extensive investigation. It is therefore more appropriate to discuss this application separately. Chapter five contains a detailed explanation of the experimental research and navigational results of system two.

CHAPTER FIVE
NAVIGATIONAL SYSTEM TWO

5.1 Introduction

In this chapter an original infrared triangulation system with high dynamic accuracy, long range and low cost is proposed. The development of system two reveals that many of the shortfalls experienced in system one have been overcome.

The attainment of acceptable accuracy would validate the proposed concept of navigation which incorporates infrared in the triangulation technique. It was considered that acceptable measurement tolerances could be attained by utilizing the same concept of triangulation as implemented in system one. The factors most influencing accuracy when considering static navigation are the precise measurement of the angular displacement. It was proposed that by implementing a rotating infrared transmitter and having stationary receiver beacons certain resolution problems experienced in system one could be resolved.

5.2 The Design Criteria of System 2

Taking into account the difficulties experienced in system one certain design prerequisites were specified for system two. The first criteria was that the system's total angular resolution had to be at least 0.5°. To achieve dynamic accuracy, the positional data accumulation had to be acquired without the AGV traversing a large linear displacement. The resultant effect is that a faster rotating beacon speed is required. For a vehicle speed of 0.1 metres per second a positional data accumulation rate of one co-ordinate point per second was found to be acceptable. However, certain complications occur when attempting to implement an increased rotating directional beacon.

Associated with a rapid directional rotating beacon, is a shorter exposure time between infrared transmission and receiving. The outcome is either a faster data transfer rate being required or less data being transmitted. System two effectively reduced the necessary amount of data to be transferred. This implied that similar conventional infrared components and circuitry could be implemented. The infrared receiver initially chosen (Part number: IS 471F, Spectratech, 1992) was effectively implemented in System two. The response time of 800 microseconds proved effectual in this application.

Using the above-mentioned strategy, system two was developed. This validated the accuracy and functionality of implementing infrared light in the concept of triangulation. It was decided to implement a rotating infrared transmitter and fixed stationary infrared receivers. This resolved the predicament of each beacon requiring an identifiable transmission signature as was the case in system one. This occurred as each activated receiver beacon could be identified individually by the controlling computer. The controlling computer could then associate each beacon with its corresponding co-ordinate position. Through eliminating the unique superimposed beacon frequencies the receiver response time could be reduced to a maximum identification time of 800 microseconds.

The activation of these beacons functioned in the following manner. Upon a stationary receiver beacon being energised with infrared light from the rotating transmitting beacon, a signal was sent to a unique CAP input port. The beacon's co-ordinate locations were specified together with their associated input ports. When an input port was activated the specific beacon's location, together with the precise duration time recorded from the previously activated beacon, were stored. This stored data was used for computational calculations of positional determination. The angular displacements between the beacons with reference to the AGV were calculated. This was accomplished by utilizing the precise measured time between activation of two beacons and multiplying this time by the velocity of the rotating transmitter beacon.

5.3 Hardware Design and Construction

The onboard navigation hardware consists primarily of a stepper motor, its driver circuitry and a rotating beacon with its associated infrared transmitter circuitry. The offboard navigation hardware consists of three receiver beacons, timers and interface circuitry. The offboard and onboard computers perform the navigational calculations and data transmission necessary for navigation.

5.3.1 Stepper Motor Driver Circuitry

A 0.5 ampere, 200 pulses per revolution stepper motor is driven from a 12 volt supply. A 4.7Ω resistor limits the current passing through the stepper motor windings. Each pole of the stepper motor windings is driven through separate transistors which switch these separately in a unipolar fashion. A 555 timer/oscillator is configured in an astable mode and supplies a constant 720 Hz pulse train. A cmos 4035 shift register converts these pulses into four separate outputs (Harris Corporation, 1992). This occurs in a sequential fashion. The shift register drives the stepper motor windings through TIP 120 darlington transistors (Towers, 1985). The cmos 4035 has the properties of internal current limiting. The output current is limited to 20 milliampere and therefore the transistor saturation current and motor current remains as described in section 4.6.1 (Harris Corporation, 1992). A schematic diagram of this circuitry is shown below.

This predefined frequency configures the stepper motor to a constant rotational speed of 3.6 revolutions per second. A toothed belt drives the rotating beacon through a ratio of 3.6:1. This results in a rotational beacon speed of 1 revolution per second.

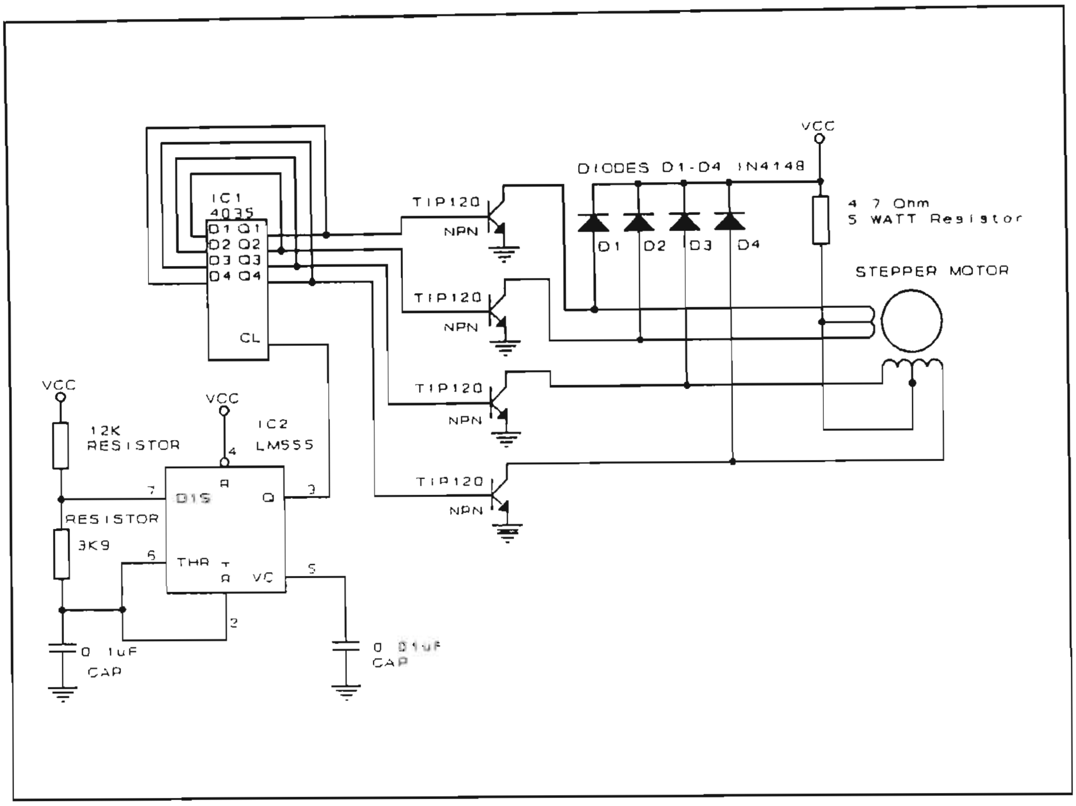


Figure 5-1: Schematic Diagram of Stepper Motor Driver and Control

5.3.2 Infrared Transmission

The infrared transmitting circuitry is located inside the rotating transmitting beacon onboard the AGV. As the beacon constantly rotates, two slip-rings are provided between this and the AGV. Power is supplied via these slip-rings to the rotating circuitry. A 38 kHz pulse train is generated inside the rotating housing using a 555 timer. These pulses drive an infrared emitter (Part number: TSUS 5402, Spectratech, 1992). A power mosfet (IRF 520) is implemented to supply the high on current required for powerful infrared emission. The resultant pulsed wave form excites the infrared emitter with an on current of 1 amp within a 10 percent duty cycle. A schematic diagram of this circuitry is shown below.

This emitted beam is focused into a vertical plane approximately 4 millimetres wide. The resultant emitted beam is 4 millimetres wide with a vertical emission angle of 25° from the horizontal plane. This allows for a variation in the vertical height placements of the beacons with respect to the AGV. The resultant vertical infrared light plane has a rotational speed of 2π radians per second (1 revolution per second). This plane activates the beacons when facing directly towards them.

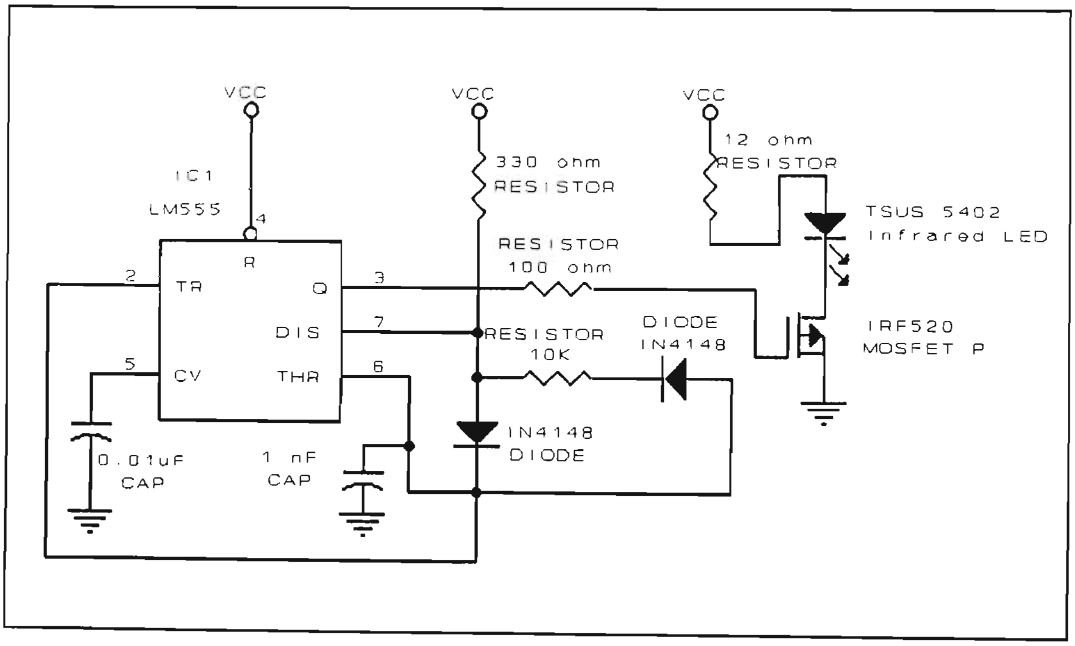
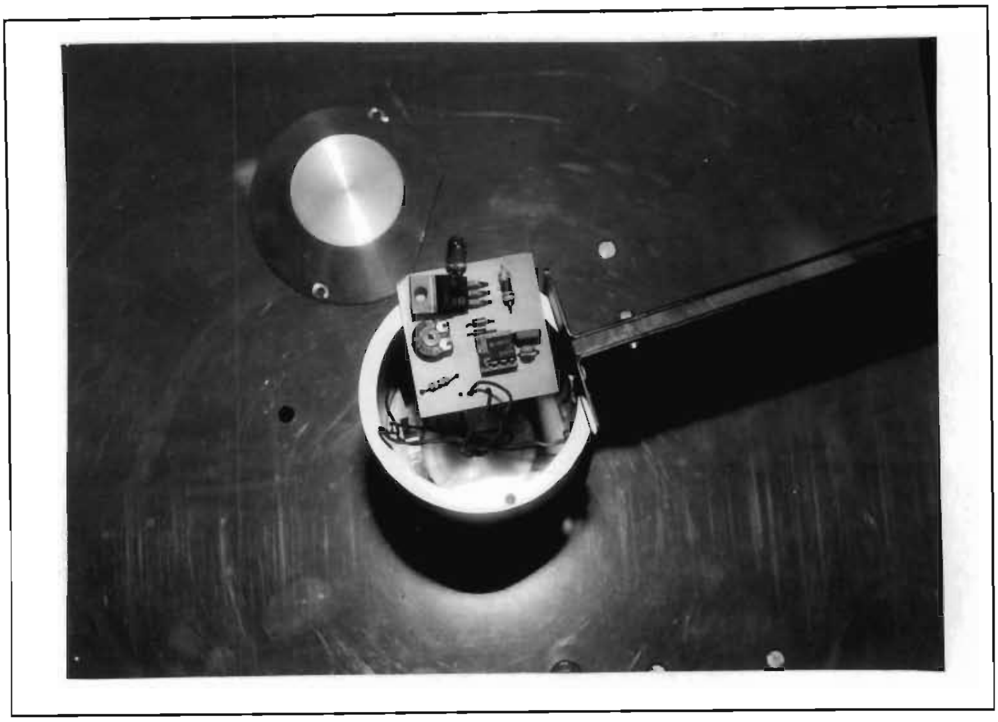


Figure 5-2: Schematic Diagram of Infrared Transmitter Circuitry



Photograph 5-1: Photograph of Infrared Transmitter Circuitry

5.3.3 Infrared Receiver Beacons

Four infrared receivers and filters (Part number: IS 471F, Spectratech, 1992) were implemented as stationary receiver beacons for the purpose of receiving and decoding infrared light. One of these receivers was utilised as the rotating receiver beacon in system one. An explanation of the circuitry was detailed in section 4.5.2. Similarly, incoming light signals with frequencies ranging from 36 kHz to 41 kHz produced a resultant output logic signal. The maximum decoding time of 800 microseconds is the predominant delay affecting this second navigation system. The result is a considerably faster response time for angular measurement. The response time being 800 microseconds for the decoder circuitry and 85.3 microseconds (see section 5.3.4) for the resolution of the timers. For a beacon rotation speed of 1 revolution per second the resultant theoretical system angular resolution is 0.319°. Refer to Appendix II for calculations.

The receiving beacons are placed at predetermined fixed locations within the AGV environment. The modulated rotating light plane located onboard the AGV activates the receiver beacons when facing directly towards them. Upon activation a signal is sent from the receiver beacon to the interface circuitry. The interface circuitry measures the precise time between beacon activation. These measurements are then input to the CAP, converted to angular displacements and used for positional determination.

5.3.4 Timer Circuitry and Computer Interface

External timer circuitry is required to accurately monitor the time taken between each beacon activation. Using external circuitry precise time measurement may be monitored without relying on internal computer timers and computer interrupts. These can cause time measurement delays as explained in section 4.8.3. The external timers used in this application were contained in an Eagle Electric Multi I/O add-on card. This plugged directly into the 8086 motherboard bus. The card offers 48 I/O lines and 3 external timers. Each timer has its own software or hardware programmable configuration. The first timer is used as a 2^{10} divider. This divides the computer clock frequency from 12 MHz to 11.71875 kHz. This is then the base timer counter frequency used. The effect is that the two remaining timers count a frequency of 11.71875 kHz whenever their associated 4013 flip-flops are in a high state. Each of the four beacon inputs are also directly coupled to separate input ports of the I/O card. This accomplishes the task of the computer being able to identify each beacon individually (Eagle Electric, 1991). The timer interface circuitry is configured in the following manner. Four beacons are placed in an AGV navigating environment. Each beacon has a unique defined location with cartesian co-ordinates with respect to a known origin. These beacon co-ordinate locations are stored in a navigational subroutine database and are used for AGV positional determination as demonstrated in the resection algorithm.

The following is an account of the sequenced logic used to start, stop and reset the timers. The external timer circuitry 'OR's' all the beacon signal input lines. This function is achieved using a 4072 cmos 4-input 'OR' gate (Harris Corporation, 1992). Furthermore, each beacon has an identifiable input to the timer interface circuitry. When infrared light strikes a beacon a signal is sent to the external timer circuitry. Upon any beacon activation the output from the OR gate triggers a one-shot timer for 10 milliseconds. This allows sufficient time for the computer to register the interrupt command signal. The interrupt initializes a subroutine to interrogate the input ports and determine which beacon has been activated. Each beacon is individually identified. The first signal identified in this process is labelled beacon one. This signal starts both external timers. The second signal identified is labelled beacon two and this stops the first timer. The third signal identified is labelled beacon three and this stops the second timer. Both time values are then input into the computer.

To determine the angular displacement between two beacons the angular velocity of the rotating beacon is required. This was predefined by the astable timer frequency output (720 Hz) which pulsed the stepper motor. This maintained a constant rotational speed of the rotating housing. The angular displacement was therefore calculated by multiplying the angular velocity by the time of activation between two beacons. The following formula is implemented to determine the angular displacement of two beacons with respect to the AGV.

$$\text{Angle } (\alpha) = \text{speed of rotation } (\Omega) * \text{time (sec)} \quad . \; . \quad \text{Eqn 11}$$

The nature of triangulation demands that a minimum of three beacons must be identified for position recognition. The angular displacements together with their specific associated beacon locations were implemented in a navigational subroutine. These values were utilized in an algorithm, derived from resection theory. This determines the x, y co-ordinate positions. The resultant vehicle co-ordinates are transmitted via radio link to the AGV for use in the guidance algorithms. The AGV position is superimposed on the digitized map layout displayed on the CAP video screen.

On completion of this process the external timers are reset in preparation for the same process of positional determination to be repeated. A schematic diagram of the circuitry used to interface the beacons, timer circuitry and CAP is presented below.

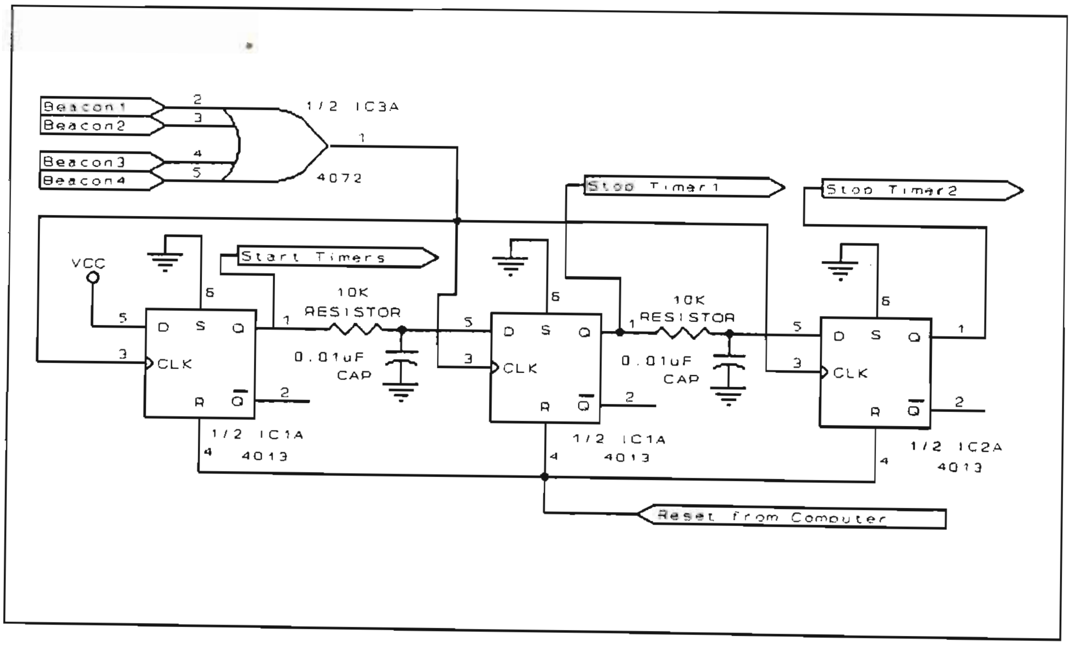


Figure 5-3: Schematic Diagram of Timer Controller

5.4 Results of AGV Navigation

Once a workable system had been constructed tests were conducted to verify the practical implementation of the navigation system. The nature of guidance in this application defined a course and fine guidance strategy. Dynamic navigation is associated with a course guidance strategy and static navigation with a fine guidance strategy. Due to this definition, static and dynamic navigation tests had to be verified separately. The angular resolution and spatial resolution for static navigation are discussed followed by a presentation of static navigational results. The factors influencing dynamic navigation are examined followed by a presentation of the dynamic navigation results. In addition, repeatability tests for a path definition are presented. These results confirm a workable navigation system that could have a direct application for free-ranging AGV movement.

5.4.1 Angular Resolution

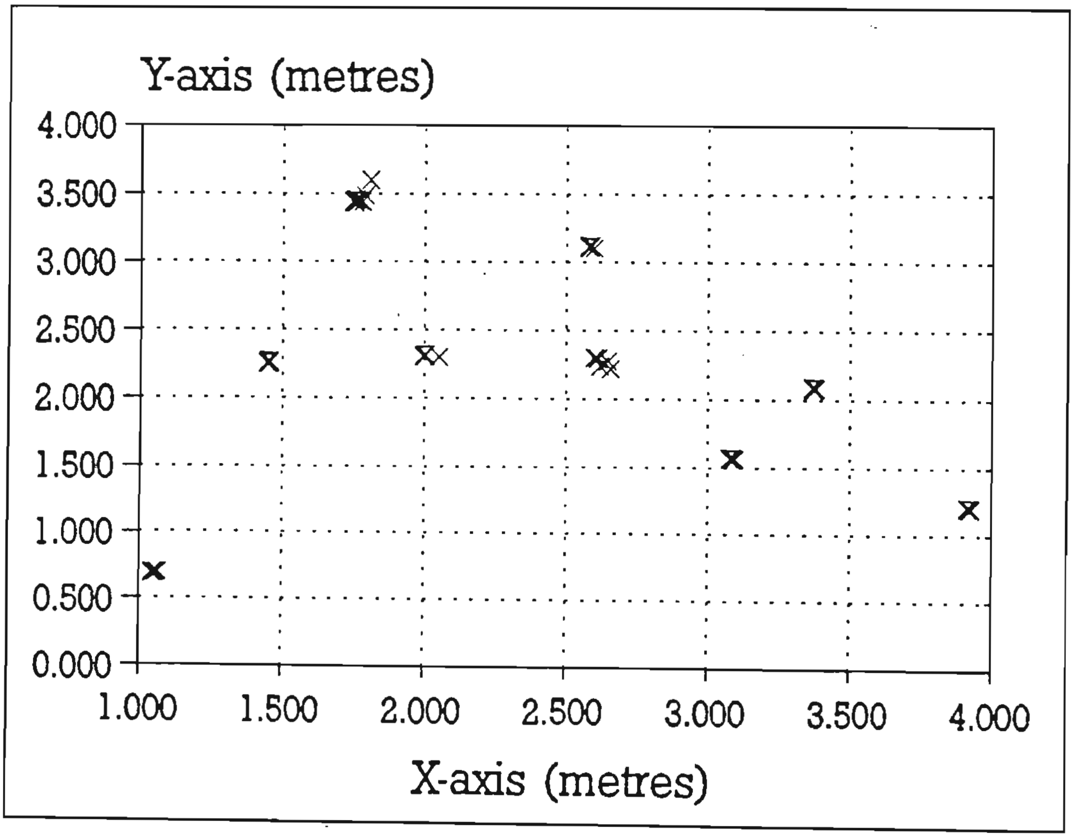
The angular resolution of a navigation system can be defined as the smallest angular increment which can be measured. In this research application the angular increment is dependent on the accuracy and duration of the smallest timing increment and the response time of the infrared receiver. Furthermore, it is dependent on maintaining a constant angular velocity of the rotating beacon. The timer frequency was set to 11.71875 kHz. The frequency input can be considered accurate as it is based on the CAP clock frequency of 12 MHz. Applicable to this navigation concept this frequency may be considered precise. The variation of the angular velocity of the rotating beacon was totally dependent on the astable timer output frequency. This frequency was used to pulse the stepper motor which maintained it at a constant velocity. Although this frequency was initially set to 720 Hz, testing revealed variations. The frequency output was monitored with a frequency counter while subjecting the astable timer to different ambient temperatures. These temperatures were applied from 18° to 24° with a corresponding output frequency varying up to 10 Hz. It was established that the ceramic timing capacitor which was initially chosen for the astable timer circuitry was unsuitable. This was later replaced with a polycarbonate capacitor chosen for its properties of excellent temperature stability. The capacitor stabilized the output frequency rendering it far less susceptible to temperature changes. Once these tests were completed the frequency outputs from both the CAP crystal oscillator and the astable timer could be considered to be precise for this application. A theoretical angular resolution could now be established. The timer input frequencies were set at 11.71875 kHz resulting in an increment period of 85.3 microseconds. This period was the resultant smallest timing increment. Applying this delay period and the response time of the infrared receiver a resultant angular resolution of 0.319° was determined. These calculations are presented in Appendix II.

The prerequisites laid out in this research in section 4.8 stated that if an angular resolution of 0.5° could be attained then acceptable static navigational tolerances could be realised. Applying these criteria to the above results determine that the resultant angular system resolution is acceptable. This is assuming that all other influencing factors are negligible by comparison. Verification of these practical results is demonstrated graphically in the following sections.

5.4.2 Overall Static Navigational Accuracy

The available working area specified for the AGV measured 4 metres by 4 metres. To validate the static navigation accuracy ten location points were chosen within the AGV's working area. At each of the locations ten independent static co-ordinate readings were taken using the navigation system. Each of the co-ordinate points was stored in a data file in the CAP. Considering the one hundred co-ordinate points taken, the following may be deduced. The maximum deviation error from the known static AGV location (worst location case) was 29 millimetres in the X-direction and 81 millimetres in the Y-direction. The minimum deviation error from the known static AGV location (best location case) was 5.9 millimetres in the X direction and 3.9 millimetres in the Y direction.

The co-ordinate positions were plotted graphically. Each of the co-ordinate data points representing the navigational positions are displayed on the graph. From this graph, an indication of accuracy as well as navigational repeatability can be ascertained. The consistency of each measured position compared to the theoretical position of the stationary AGV is indicative of static navigational repeatability. This is detailed in the discussion in chapter six.



Graph 5-1: Graphical Representation of Static Repeatability at Various Positions within the AGV Navigation area

Once the overall static navigational accuracy had been tested further analysis into the spacial resolution of each co-ordinate position was investigated.

5.4.2 Static Navigational Spacial Resolution

Navigational spacial resolution is defined as the maximum tolerance of the navigation system. This tolerance value can be attained through measuring the maximum deviation of multiple recorded navigational readings when taken from the same physical co-ordinate position. The spacial resolution is consisted of the combined inaccuracies of the system. These include the control resolution and errors originating from the dynamic interaction of the AGV within its environment. Many factors can be attributed to these inaccuracies. A major influence being the total angular resolution of the navigation system. This encompasses errors stemming from temperature affecting the stepper motor driver electronics. The effect of this temperature change alters the rotating beacon speed. It should be noted that this source of error has largely been reduced in the electronic drive circuitry. An additional error originates from the truncation of arithmetic floating point calculations. This truncation results in navigational inaccuracies which occur due to the limitations of the microprocessor in dealing with large floating point numbers when performing arithmetic calculations. These miscalculations are amplified whenever the angular measurement between two beacons with respect to the AGV approaches 180°. This occurs because the trigonometric tan function is implemented in the navigational algorithm. The value of this function approaches zero as the value of the measured angle approaches 180° resulting in the resection formulae calculations approaching infinity (see section 4.8.1).

Two co-ordinate points were measured within the AGV navigation environment. For each test conducted the centre of the AGV navigation system was located on these measured co-ordinate points. Eleven navigational co-ordinate readings were recorded at each co-ordinate point. These co-ordinate values were exploded onto separate graphs as is represented below. It should be noted that the nature of the working environment rendered it difficult to measure the precise real physical co-ordinates of these location points. The reason for this being that the difference between the theoretical and measured co-ordinate points (i.e. navigational accuracy) was less than the variance between the physical walls and the theoretical co-ordinate axes. This is explained diagrammatically in Figure 5-4.

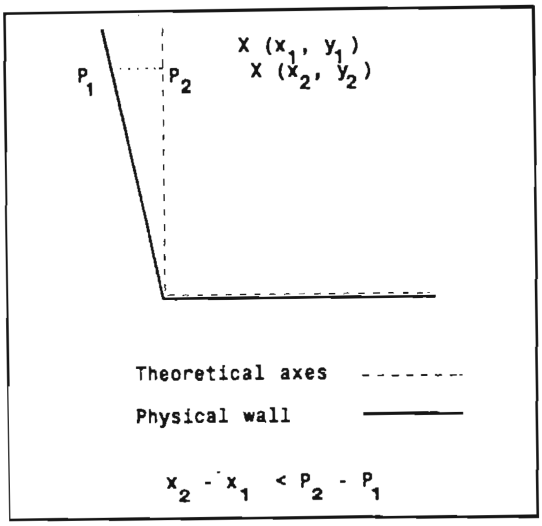
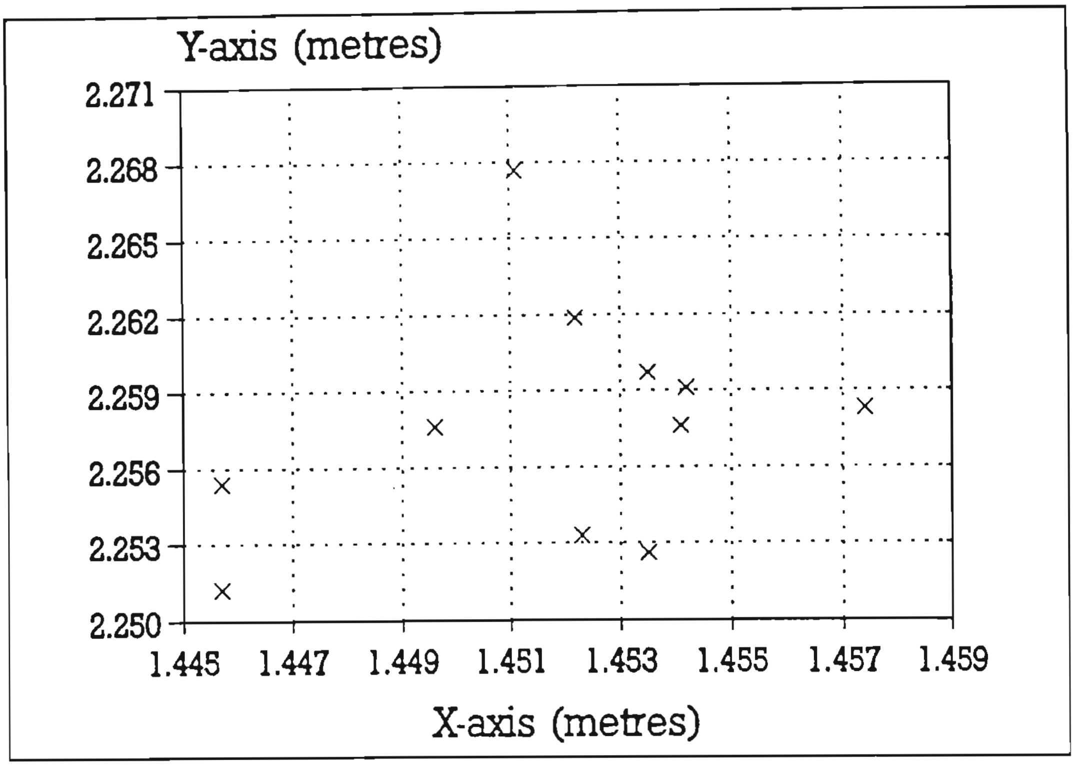
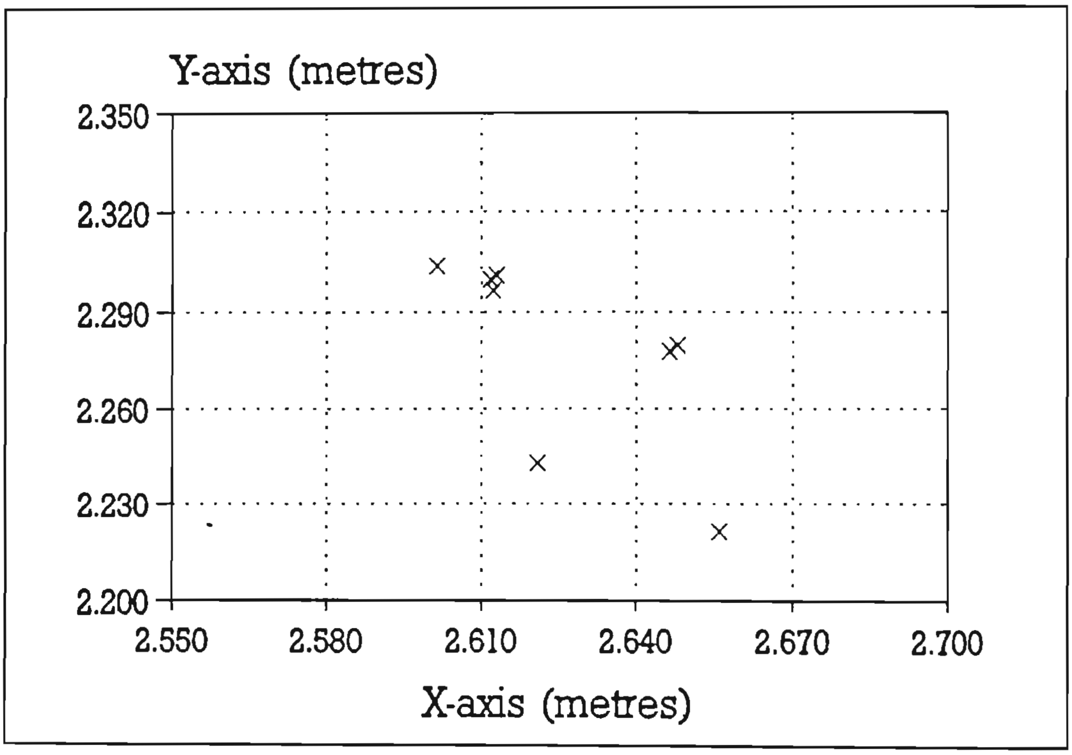


Figure 5-4: Diagrammatic Representation of Co-ordinate Measurement Errors

Once this system proved to be functional under static navigation conditions it was necessary to ascertain its practical ability when subjected to dynamic working conditions. In determining dynamic navigational accuracy there are two relevant factors to consider. These are the speed of the vehicle and the time taken to assimilate a navigational data point. Tests were conducted monitoring the dynamic movement of the vehicle by plotting its navigational points along its path of movement.



Graph 5-2: Graphical Representation of Spacial Resolution (best case)

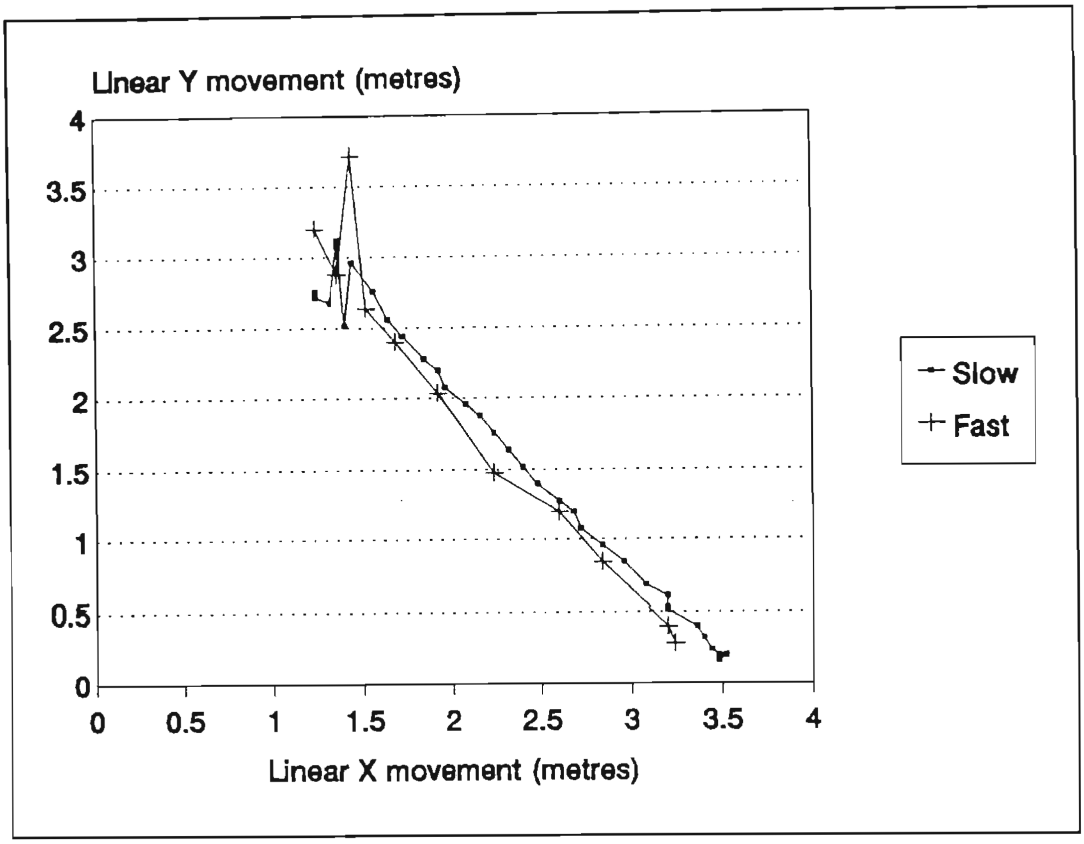


Graph 5-3: Graphical Representation of Spacial Resolution (worst case)

5.4.3 Navigational Data Accumulation Rate

The data accumulation rate is dependent on the speed of the rotating turret (one revolution should result in one set of co-ordinates). For the first navigation system the speed of beacon rotation was 7 seconds. This speed gave the decoder enough time to interpret a transmitted signal. The second system had a turret rotation speed of 1 revolution per second. This resulted in a data accumulation rate of 1 reading per second. The vehicle's maximum velocity was 10 centimetres per second. Referring to equation 10 indicated that the resultant dynamic accuracy was 10 centimetres at maximum speed. This formula is based on the assumption that a navigational reading is accumulated on completion of a revolution. However, in practice a navigational data point is accumulated in less time than the full revolution of the rotating beacon. For this reason the dynamic tolerance of the navigation system should be less than the value determined by equation 10. Further tests were carried out employing a faster rotating beacon. These tests showed promising results. It was found that at a range of 5 metres between infrared transmitter and receiver, the rotating beacon speed could be reduced to half a second per revolution.

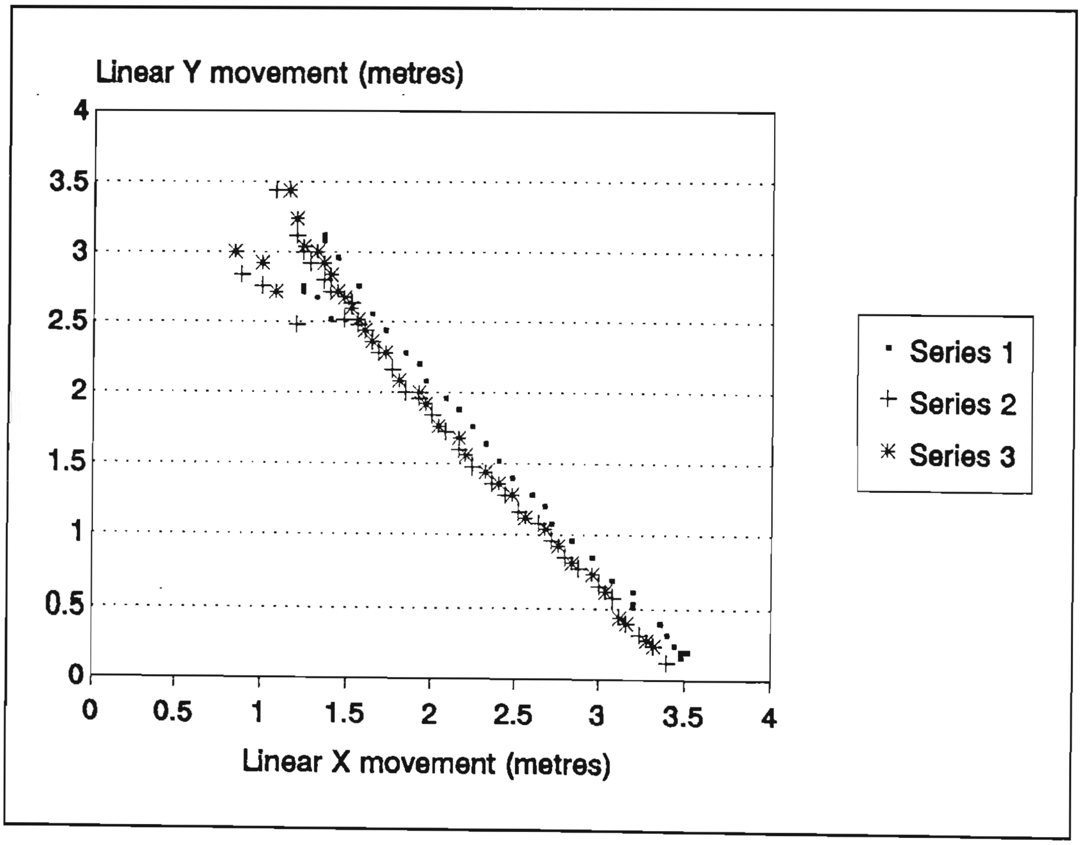
A test was carried out to investigate the decrease in dynamic accuracy corresponding to an increase in vehicle speed. Two similar paths were traversed by the AGV. One at a speed of 0.03 metres per second, the other at a speed of 0.1 metres per second. The correlation coefficients of these two routes were then compared. The resulting slow correlation coefficient was 0.992 and for the faster speed a lower correlation coefficient of 0.980 resulted. This is an indication that the dynamic accuracy decreases with an increase in speed as confirmed by equation 10.



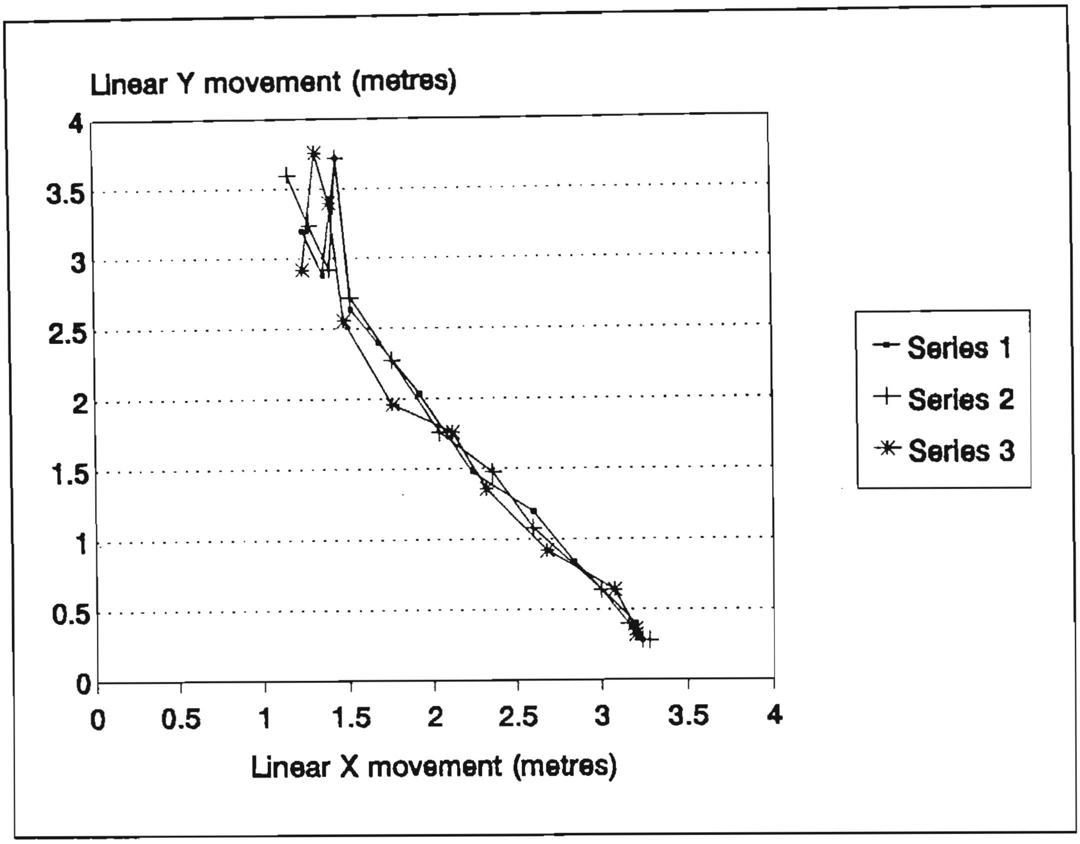
Graph 5-4: Comparison of Navigational Co-ordinates for Velocities of 0.03 m/sec (slow) and 0.1 m/sec (fast).

5.4.4 Dynamic Navigation Repeatability

Dynamic navigation repeatability is defined as the measure of repeatability to which the navigational system maps path co-ordinate readings. Tests were carried out to monitor AGV movement along a predefined route. Three AGV paths were chosen within the navigation working area. The vehicle traversed each of these paths three times and the navigational co-ordinate positions of the vehicle movement were plotted for each path. This was accomplished for a speed of 0.03 metres per second. The effect of a faster speed of 0.1 metres per second was then investigated. In practice it was difficult for the AGV to traverse the identical path in the same manner. This difficulty is indicated by the fact that the AGV plotted a different path for each route. Upon referring to Graph 5-5 the correlation coefficients for the navigational recordings for three AGV traverses while travelling at 0.03 metres per second are 0.992, 0.988 and 0.989. The correlation coefficients of the three faster navigational readings of 10 centimetres per second resulted in lower values of 0.973, 0.980 and 0.960. This is an indication that the navigational resolution decreases with an increase in speed.



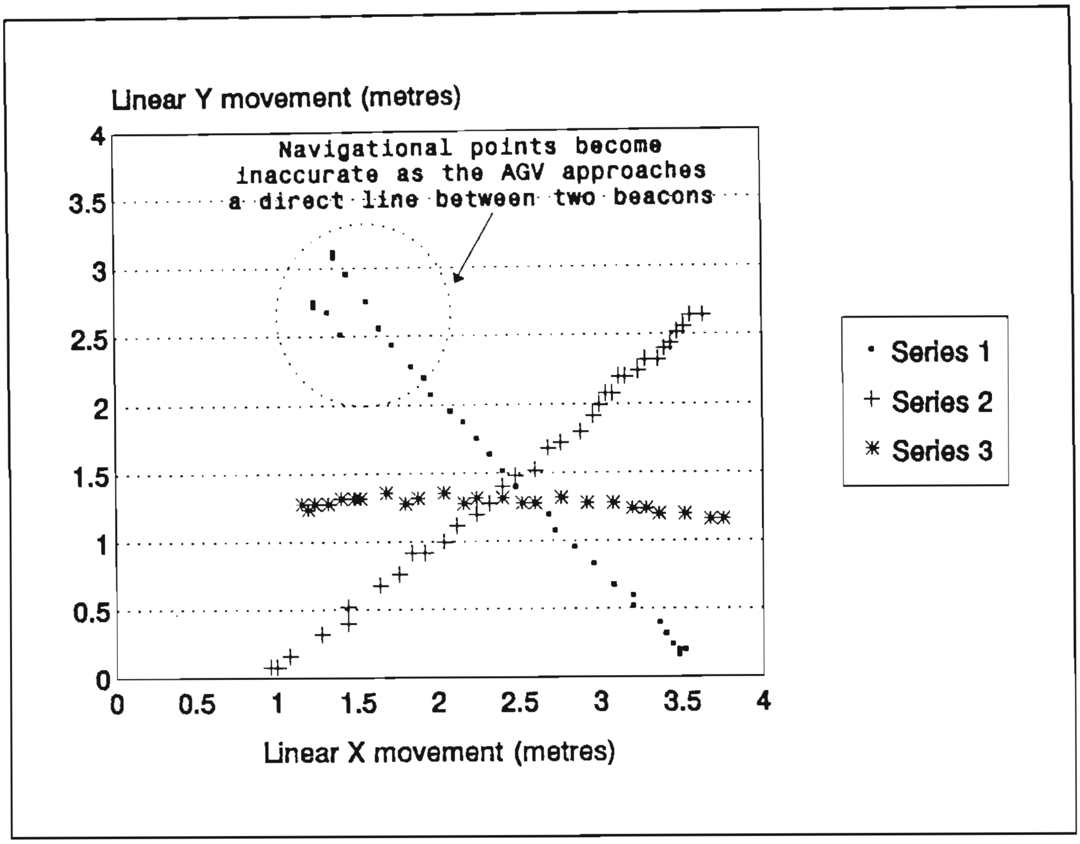
Graph 5-5: Graphical Representation of Dynamic Repeatability (Velocity 0.03 metres/second)



Graph 5-6: Graphical Representation of Dynamic Repeatability (Velocity 0.01 metres/second)

5.4.5 Dynamic Navigation Inaccuracy

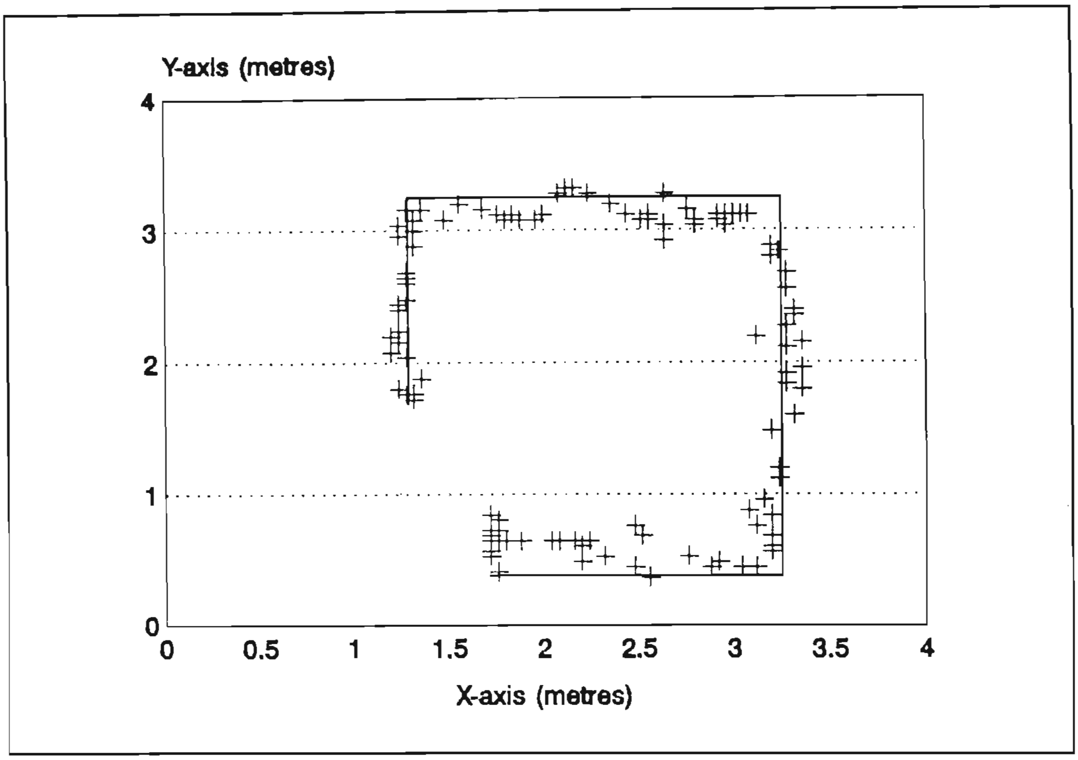
Dynamic navigation inaccuracy tests implemented a vehicle speed of 0.03 metres per second. Three different paths were traversed within the AGV navigation area. One of the paths chosen to be traversed was through a direct line between two beacons. As can be seen in the navigational results below as the AGV approached this zone the resultant positional co-ordinate readings became increasingly erratic. This is evidenced from the discussion in section 4.8 which details the occurrence of these computational errors.



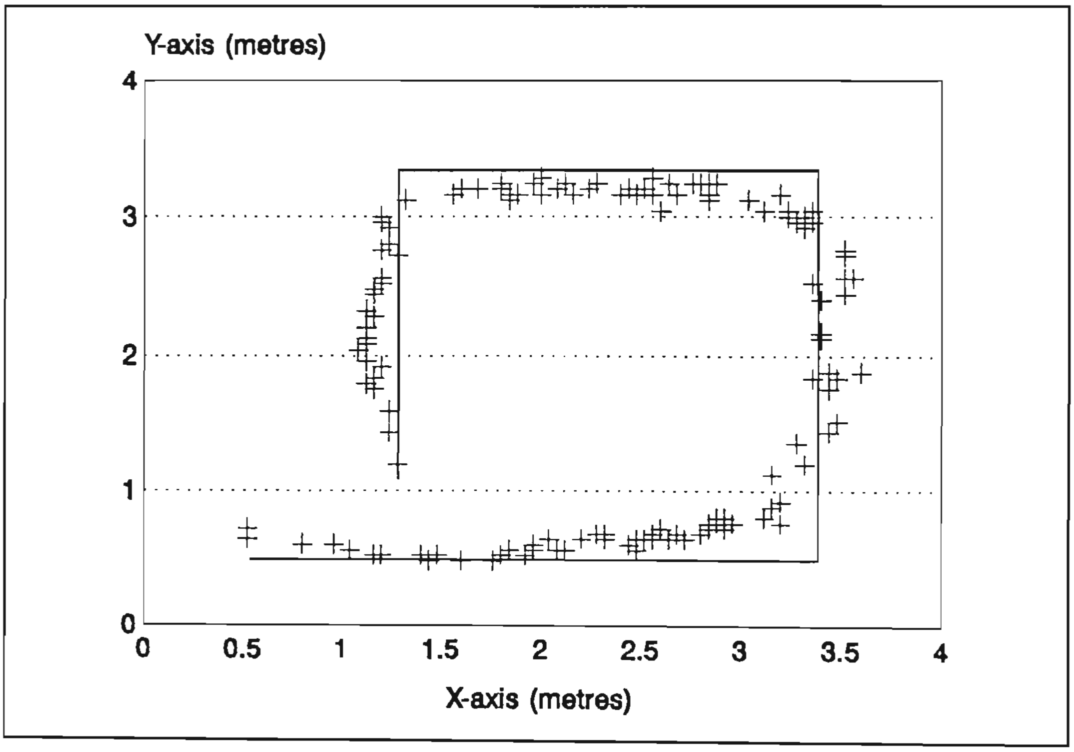
Graph 5-7: Graphical Representation of Three AGV Navigational Co-ordinate Paths

5.4.6 Guidance Results

Once the navigational system had been verified practically the guidance strategy detailed in Chapter 3 needed to be tried and tested. A route was selected on the CAP screen and downloaded via radio link to the AGV. The guidance strategy was utilised onboard the AGV to manoeuvre the vehicle along this route to the requested destination. The AGV followed this predefined route at a vehicle speed of 0.03 metres per second, whilst continually acquiring positional data points from the navigational system. These data points were received from the CAP via the communication link and implemented in the guidance strategy. This AGV movement was recorded using the navigation system and plotted graphically. This procedure was undertaken twice and is represented graphically below.



Graph 5-8: Graphical Representation of AGV Movement whilst Utilising the Guidance Strategy



Graph 5-9: Graphical Representation of AGV Movement whilst Utilising the Guidance Strategy

CHAPTER SIX

6.1 Discussion

A discussion of the various aspects of this research application is detailed. An explanation of the communication system and its resulting functionality is presented and interpretation of the navigational results are shown. This includes an account of static and dynamic navigation. This lays the foundation for the final discussion of guidance results. Navigational data is implemented in effecting the correct guidance procedure.

6.2 Communication

As stated by Litwin (1992) 'the more exotic you make a modem to improve its theoretical bit rate the less well it will perform in noise, hence the greater communication overhead required'. The choice of FSK for data transmission was fundamentally the correct decision as it satisfied the criteria of duplex wireless communication. However, an improved modem design with a higher baud rate could prove advantageous in some free-ranging AGV wireless communication applications. The duplex communication developed in this research functioned adequately for its specific application. This duplex communication could be inapplicable in some unusual circumstances. An example of this is when more than ten vehicles are required to operate in a given area, or in environments where interference may occur with radio transmission. Given these conditions, specialized communication techniques should be investigated.

A multipath propagation model specifically for in-building communications and its application to AGVs has been developed. This model developed by Rappaport and Seidel (1989) investigates wideband wireless networks for AGV communication. Their research focused on the simulation and effects thereof, of transmitter receiver distance and receiver sensitivity (Rappaport & Seidel, 1989).

FM radio frequency as a wireless communication medium proved effective and successful. The choice of VHF FM radio frequency operating at 144 MHz as a carrier frequency overcame problems of 'beyond direct line of sight'. This is commonly associated with low frequency FM radio communication. Reliable two way communication beyond direct line of sight proved successful. Test data was transferred over acceptable ranges and in typical manufacturing environments. The test results obtained surpassed the expectations defined at the outset of this research. The use of VHF in obstacle penetration proved adequate for the conventional application of AGVs. It is suggested that in unusual circumstances of major obstructions between transmitter and receiver, UHF as a communication medium should be implemented.

In certain cases a higher baud rate could alleviate communication congestion. This is especially the case where high overheads are encountered from re-transmission requests. It was found that the overheads increase when attempting to transmit at the limits of the communication range. This is because the transceivers consume communication time with re-transmission request signals. As stated by Litwin (1992) above, care should be taken not to over design a modem with the aim of achieving a higher baud rate. Various other radio communication procedures are available that can increase the data transfer rate. One such available method is the 'spread spectrum technique'.

The objective of the first communication test was to prove that duplex wireless communication over acceptable transmission ranges is possible and practical. The test verified this possibility by transmitting and receiving over a 400 metre span with error free data transfer. The second test confirmed the advantages of using VHF FM as a radio medium for out of 'direct line of sight' two way communication. The tests were conducted in conditions similar to those of an AGV operating in an industrial manufacturing environment. The AGV manoeuvred around obstacles and machines going beyond the direct line of sight of its respective communication transceiver. During this operation 100 percent error free duplex communication was achieved where the parameters of AGV movement were not more than 40 metres. Test three subjected the communication to adverse conditions. This data transfer occurred through a total of 90 centimetres of cement and through two adjacent laboratories. These tests were conducted over a range of between 40 metres and 60 metres. A result was that the data transfer integrity degraded rapidly with distance (declining from 100 percent communication at 40 metres to 52 percent at 60 metres). This is represented graphically in Appendix I. In the final test duplex communication was subjected to similar conditions to those conducted in test three. However, this test added the extra interference of two operating manufacturing machines. These machines were a Maho CNC milling machine and a Boehringer Goppingen 15 kW lathe. These machines had no noticeable effect on the communication system.

6.3 Navigation

The use of infrared as a medium for navigational information transfer within a manufacturing environment is possible and advisable. No external interference is probable if correct signal coding procedures are adhered to. An infrared transmission range of 5 metres was used in this research application. However, utilizing the correct operating procedures and careful selection of infrared transmitters, longer ranges can be expected. Most infrared transmitters supply the same power output and therefore the correct balance between spectral angle and spectral transmission intensity must be chosen. The minimum spectral angle that should be used is 50° in order to achieve sufficient floor coverage. However, angles of up to 130° in infrared transmitters are available (Siemens part number SFH 487 P-1).

The correct incorporation of infrared and triangulation can result in an accurate navigation system for free-ranging AGVs. From theoretical calculations it was found that, in a 4 metre by 4 metre area, a maximum error tolerance of 0.5° in angular measurement would result in a maximum deviation in the X-direction of 23 millimetres and in the Y-direction of 46 millimetres. This was based on a theoretical case where the navigational measurement system was placed at the epicentre of an equilateral triangle. Due to the resulting large inaccuracies in angular measurement in system one the development was rendered inadequate for free-ranging AGVs. The theoretically calculated angular resolution of system one was shown to have a maximum tolerance of 4° (for a rotating angular beacon speed of 51.4 degrees per second). This resolution resulted in a possible linear tolerance in the X-direction of a 193 millimetres and in the Y-direction of 370 millimetres. Although these tolerance levels are unacceptable for free-ranging AGV navigation, the practical test results were even more unsatisfactory and therefore there was no point in recording these values. However, experience in this field led to the development of system two.

This system operated successfully under static and dynamic working conditions. A data accumulation rate of one co-ordinate position per second was achieved. A theoretical angular resolution of 0.319° was calculated and this was verified in practical results. The practical results for static navigational accuracy are presented in Chapter 5. Ten navigational points were selected and ten readings were taken for each point. The most favourable result was a maximum navigation tolerance limit of 5.9 millimetres in the X-direction and 3.9 millimetres in the Y-direction (see graph 5-2). The worst result obtained for ten readings on a static navigation point was 29 millimetres in the X-direction and 81 millimetres in the Y-direction (see graph 5-3).

From equation 10 the resultant theoretical dynamic tolerance was 10 centimetres for a maximum vehicle speed of 10 centimetres per second and a navigational data accumulation rate of one data point per second. This dynamic tolerance value did not include factors such as the resultant variation in angular measurement due to the movement of the vehicle while attempting to accumulate a data point as well as temperature instability effects. Even taking these factors into account the dynamic tolerance reading did not vary more than 10 centimetres. This can be attributed to the fact that although the navigation beacon rotated at one revolution per second the navigational positional reading is completed after passing the third beacon. This is always less than one second. This action resulted in a faster positional data accumulation rate and hence better accuracy. Tests were recorded for varying vehicle speeds. The decline in dynamic accuracy with speed was verified by comparing the correlation coefficients of a fast and slow moving vehicle (10 centimetres per second and 3 centimetres per second). The AGV traversed a path which converged on a point which lay directly between two of the beacons. As the AGV approached this point the navigational readings became erratic. This verified the claim made in section 4.8.1 that inaccuracies will arise as the AGV attempts to navigate along a path that falls in a direct line between two beacons.

Finally, the navigational data readings were incorporated into the guidance strategy. The AGV was requested to manoeuvre along a given route and utilized the guidance strategy in order to maintain its movement along this route. The AGV path was plotted from the navigational readings and this path was compared with each requested route segment.

Due to the slow response of the vehicle drive mechanism, larger inaccuracies than were originally conceived were experienced. The maximum difference between requested route and AGV path was 30 centimetres. From these results the guidance strategy proved successful. However, improved guidance algorithms should be investigated for efficient motion control.

6.4 Conclusion

A free-ranging AGV was developed that incorporated the concepts of radio communication, wireless navigation and a guidance technique. A radio modem was designed, built and successfully tested. Two way wireless radio data transfer offered many more advantages than other wireless communication links. It is therefore recommended for free-ranging AGV communication.

Two infrared navigational techniques have been applied in this research. The originality in this research is in triangulation using infrared, as opposed to radio or ultrasonic transmission mediums. Comparatively low levels of interference were achieved with signal conditioning and filtering. Original methods of beacon identification are suggested to eliminate interference as well as incorrect beacon identification. Two navigation systems were investigated using infrared triangulation. The first requires some improvement for practical application. The second systems test results exceeded accuracy criteria while still achieving the advantages of low cost, minimal interference, ease of installation, adaptability and maintaining acceptable range. The aim of this research was not to design an AGV for operation in a multi-AGV environment. A FMS usually requires more than one AGV for materials handling. Given that this navigational system was inapplicable for multi-AGV navigation, a third system is suggested (section 6.5.1). This technique proposes the advantages of possible implementation in a multi-AGV environment, however, careful design and possibly specialized components may be required. The use of infrared triangulation as a navigation technique and the implementation of the methods suggested herein renders this form of navigation system applicable for free-ranging AGV operation.

The guidance algorithm was verified and test results presented. Modification of the guidance algorithm is suggested to achieve efficient motion control. It is considered that implementing the conceptual method of course and fine guidance with this form of navigation will suffice in most free-ranging AGV applications.

In conclusion a free-ranging AGV was built and tested. During the basic guidance testing, AGV path tracking was verified. The communication and navigation results prove that this is a workable system that could readily be applied to a manufacturing environment.

6.5 Recommendations for Further Work

6.5.1 System 3

System 1 proved unsuccessful when applied practically. It was considered that the conceptual design would be workable if improved functionality could be achieved. System 2 verified this supposition by fulfilling the requirements of this research application. This was to develop an accurate navigation system which is easily implementable, modifiable and accurate being of low cost and having minimal interference and long range. However, due to the shortfalls experienced in the two navigation systems, a third system was proposed which encompasses the benefits of the first two systems.

It is proposed that a universal system is developed that incorporates the concepts of system 1, whilst still maintaining the accuracy of system 2. System 1 suggests an onboard positional co-ordinate determination system with many advantages. The main advantage being that the navigation system is located onboard the AGV and this eliminates the problem of the CAP having to transmit navigational data for each positional reading. This reduces the communication overhead between the CAP and the AGV. Another advantage of this system could be incorporated into a multi-AGV environment with each vehicle being able to access the same transmission beacons.

To achieve the accuracy of system 2, there are two major upgrades that should be undertaken. The first is that external stepper motor counters and drivers should be employed. This would reduce the overhead of the computing time of the onboard microprocessor as well as eliminate the delay arising from the microprocessor servicing the interrupts. If an 80C196 microprocessor is implemented onboard the AGV, the onboard timers incorporated in its circuitry could be implemented (section 6.5.2). This update could monitor, as well as drive, stepper motors. In addition, a precise angular stepper count could be maintained as well as immediate stepper motor angular rotation interrogation. This system would not have to rely on the slow responses of the interrupt experienced on the Intel 8086 microprocessor.

A high frequency response infrared receiver and associated circuitry would also help to improve the decoding delay of the composite received light signal. It is recommended that a 350 kHz infrared carrier signal is used as a base frequency. Investigating the calculations in Appendix II for system 3, the utilization of this carrier frequency reveals the following results. The maximum beacon frequency can be increased to 11.5 kHz. This system could then have a resultant angular resolution of 0.56° when subject to a one revolution per second rotation speed.

Care should be taken when selecting the infrared receiver because standard receivers tend to attenuate in this high frequency range around 350 kHz. As the navigation response is related to the dynamic navigational accuracy, a faster infrared light pulse will result in faster capture and decoder times and this would influence the overall effectiveness of the system. Careful design procedures should be adhered to when designing the infrared decoder circuitry. An effective automatic gain adjust is needed to respond to the varying strength of the infrared spectral input as the receiver and transmitter vary in span. Infrared transmitters are available with a 130° spectral angle. This increases the available floor coverage for each transmitter beacon but care should be taken that the spectral power intensity is not reduced excessively. This would limit the range between transmitter and receiver. It is considered that with the correct design procedure a multi-AGV navigation system incorporating accuracy and flexibility may be achieved.

6.5.2 Onboard Microprocessor

It is recommended that the basic building block used as the AGV microcontroller should be upgraded to one of the 80C196 Intel microprocessor family. These are 16-bit microprocessors featuring standard onboard timers and D/A convertors in the form of pulse width modulated outputs. The implementation of this microcontroller would imply that the onboard timers could be used for accurate navigational measurement and the D/A outputs for implementation in variable speed drive controller. The high processor speed would overcome most shortfalls in arithmetic overhead, and would allow sufficient computer power for overall vehicle measurement. The power supply requirements could be reduced to a 12 volt and 5 volt supply, with the 5 volt supply requiring less than 1 ampere for overall microcontroller management. Intel's new 87C196KD is a memory upgrade for the existing 80C196 family featuring 32 kilobytes of onboard ROM and 1 kilobyte of onboard RAM. The major drawback of this microcontroller enhancement would be the loss of an easily modifiable magnetic media. This is presently onboard the AGV in the form of a floppy drive. To apply this proposal EPROM emulators would be required, as well as a high level language compiler (Chen, 1992).

6.5.3 The Modem

Normal working conditions revealed that communication congestion was not a major concern. The initial baud rate of 300 sufficed for AGV communication even though continuous navigational co-ordinates had to be retransmitted to the vehicle. It is considered that with an onboard navigational system the AGV co-ordinate position would only have to be transmitted periodically to the CAP. This would considerably reduce the communication congestion, making more communication time available. A consideration of these factors reveals that increasing the baud rate to 2400 for a multi-AGV transportation system would fulfil the communication requirements. This form of communication would suffice for up to 20 vehicles. In the uncommon case where more than 20 vehicles are required, alternative communication technologies such as packet radio and spread spectrum transmission, should be investigated.

6.5.4 Guidance

Although it is felt that the basic concept of guidance used in this research application would suffice for most manufacturing conditions, it is considered that an improved motor control should be investigated. An algorithm integrating the vehicle speed with navigational tolerance limits could enhance vehicle manoeuvring time. This algorithm should be dependent on vehicle speeds, navigational accumulation rate and navigational tolerance limits. Using this proposed algorithm, the vehicle could gradually 'home in' on its desired co-ordinate position. This would eliminate the present method of vehicle docking, whereby the vehicle physically stops and takes a navigational reading before moving to its end location point.

An algorithm interfacing the speed of the vehicle with its corresponding deviation from its desired position should be formulated. This would maintain a more efficient dynamic positional accuracy for the vehicle with respect to the desired route location. This could be further effected by implementing improved control of the mosfet drive circuitry. Using this optimal control, the velocity of each of the Mecanum wheels could be precisely controlled. This control would result in the vehicle being able to traverse in any direction as requested by the guidance algorithm.

REFERENCES

Arkin, R C & Murphy, R R, (1990), **Autonomous navigation in a manufacturing environment**, IEEE Transactions on Robotics and Automation, Vol.6, No.4, p.445-454.

Banta, L E, Dickerson, S L, Bohlander, R & Holcombe, W, (1987), **Reduced-Order, Extended Kalman Filter for AGV Navigation**, American Society of Mechanical Engineers.

Banta, L E, (1989), **Self-tuning Navigation Algorithm for a Robotic Vehicle**, Proceedings of the 1989 American Control Conference, Vol. 1 (of 3), p.503-506.

Bedford, M, (1990a), **Data Communications**, ETI, Vol 19 No 9., p16-20.

Bedford, M, (1990b), **Data Communications**, ETI, Vol 19 No 10., p.54-57.

Basran, J S, Petriu, E M & Groen, F C A, (1989), **Developments in the measuring of the absolute position of automated guided vehicles**, IEEE Instrumentation and Measurement Technology Conference, p.132-137.

Ben-Arieh, D, (1991), **Concurrent Modelling and Simulation of Multi-Robot Systems**, Robotics and Computer Integrated Manufacturing Vol.8, No.1, p.67-73.

Bistrack Vehicle Positioning System, (1992), BIS Baud Information Systems PTY, Limited.

Boegli, P, (1985), **A Comparative Evaluation of AGV Navigation Techniques**, Proc. of Third Int. Conf. on AGV Systems, IFS Publication, p. 169-180.

rown, M, Fraser, R, Harris, C J & Moore, C G (1991), **Intelligent self-organising controllers for autonomous guided vehicles comparative aspects of fuzzy logic and neural nets**, IEEE Conference Publication, Vol.1, No.332, p.134-9.

hanpurkar, V, (1991), **Design of Autonomous Mobile Robot for Unknown Dynamically Changing Environments**, Fourth World Conference on Robotics Research, p.11-21.

er, D H, (1989), **AGV's and new technology at Caterpillar**, SME Technical Paper.

one, J & Eman, K F, (1989), **Mobile robot routing with ynamic programming**, Journal of Manufacturing Systems, ol.8, No.4, p.257-266.

Chen A, (ed.), (1992), **80C196 Family Expanded with more Memory on Chip**, Microcomputer Solutions, Sept/Oct 92, p17-18.

Chin, T C, (1989), **Remote communications for automated guided vehicles**, ISA Calgary '89 Symposium.

City Engineering Department, (1987), **Survey Handbook**, 5th ed, Durban, Institute of Topography and Engineering.

Corran, P S, (1986), **Automatic Guided Vehicle Control and Communication Systems**, Proc. of Int. Conf. on AGVs.

Coughlin, R F & Driscoll, F F, (1987) **Operational Amplifiers and Linear Integrated Circuits**, 3rd ed, Cambridge, Prentice-Hall International.

Culley, G & Baldur, R, (1988), **Free wheel approach to AGV navigation**, Computers in Engineering 1988 - Proceedings, p.267-274.

Dayal, R, Rao, G N & Sen, A P, (1986), **Design of an Automatic Guided Vehicle (AGV)**, Emerging Trends in Manufacturing: Proceedings of the 12th All India Machine Tool Design and Research Conference, p.203-207.

Dickerson, S L, Lee, K, Lee, E H, Single, T & Li, D, (1991), **Intelligent Material Handling - use of vision**, Proceedings of SPIE - The International Society for Optical Engineering, Vol.1381, p.201-209.

Dillmann, R & Rembold, B, (1988), **Kinematic Control of Mecanum Wheel based on Omni-directional mobile platform.** International Advanced Robotics Program, University of Solford, 20:1-17.

Drunk, G, (1988), **Free-Ranging AGVs**, International Journal of Machine Tools and Manufacture, Vol.28, No.3, p. 263-272.

Dutton, B, (1990), **Moving Mountains of Fruit**, Manufacturing Systems, Vol.8, No.2, p.28-9.

Eagle Electric, (1991), **PC-14 Programmable I/O Interface Reference Manual**, Eagle Electric Co. (PTY) Ltd., Cape Town.

Evans, D F, (1988), **Lasers liberate guided vehicles**, Engineering (London), Vol.228, No.II, p.610-611.

Exar Integrated Systems (eds.), (1978), **Exar Function Generator Data Book**, Exar Integrated Systems , Inc., Sunnyvale CA.

Katz, Z & Asbury, J, (1990), **Communication and Mapping Systems for a Free-Ranging Automated Guided Vehicle**, Annals of the CIRP, Vol 40, p.471-473.

Katz, Z & Asbury, J, (1992), **On-Line Position Recognition for Autonomous AGV Navigational System**, Accepted and awaiting Publication from Manufacturing Systems Journal.

Katz, M & DeWet, A P M, (1990), **Research Work**, Mechanical/Electrical Engineering, University of Natal, Durban.

Kim, Y & Naganathan, N G, (1990), **Real time collision avoidance algorithm**, Design Engineering Division, Vol 28.

Koff, G A & Boldrin, B, (1985), **Automatic Guided Vehicles**, Materials Handling Book, Ch. 8. Wiley.

Koren, Y (1983), **Computer Control of Manufacturing Systems**, Japan, McGraw-Hill.

Leibson, S, (1989) **The Handbook of Microprocessor Interfacing**. 2nd edition, Blue Ridge Summit, TAB Books Inc.

Liu, P & Fu, L, (1989), **Planning and scheduling in a flexible manufacturing system using a dynamic routing method for automated guided vehicles**, IEEE International Conference on Robotics and Automation, Vol.111 (of 3), p.1585-1589.

Lim, R, Siong, L & Choon, H, (1989), **Development and implementation of an intelligent flexible manufacturing system**, Journal of Mechanical Working Technology, Vol.20, p.389-402.

Litwin, L G, (1992), **Radio Modems - how fast is fast?**, Mobile Data, p.26-27.

MacLeod, I M & Lun V, (1992) **Progressive Reasoning for Real-Time Intelligent Computing**, IEEE Control Systems, p.79-83.

Madwed, A, (1984), **The design and planning of futuristic factories**, Proc. Int. Conf, on Robotics and factories of the future, Charlotte, USA, p. 3-10.

Main, K G, (1989), **MAP moves 30-ton coils of aluminum**, ISA Transactions, Vol.28, No.4, p.71-74.

Mallot, H A, Zielke, T, Storjohann, K & von Seelen, W, (1991), **Topographic mapping for stereo and motion processing**, Proceedings of SPIE - The International Society for Optical Engineering, Vol. 1382, p.397-408.

Maxim Integrated Products, (eds), (1989), **Integrated Circuits Data Book**, MIP, Inc., Sunnyvale, CA.

McElroy, J F, Stephens L M, Bonnell, R D & Gorman, J, (1989), **Communication and cooperation in a distributed automatic guided vehicle system**, Conference Proceedings of IEEE - Energy and Information Technologies in the Southeast, Vol.3 (of 3), p.999-1003.

Miller, R K, (1987), **Automated Guided Vehicles and Automated Manufacturing**, Society of Manufacturing Engineers, Dearborn, Michigan 48121.

Moslier, F E & Schneider D I, (1988), **Using Turbo Basic**, California, Osborne McGraw-Hill.

Murphy, R R & Arkin R C, (1988), **Autonomous Mobile Robots in Flexible Manufacturing Systems**, Proceedings - Fourth Annual Conference on Artificial Intelligence Applications, p.412-414.

National Semiconductor Corporation, (1988), **Linear Databook 3**, Edition 1988, Santa Clara, USA.

Nielsen, L, (1988), **Automated Guidance of Vehicles Using Vision and Projective Invariant Marking**, Automatica, Vol.24, No.2, p. 135-148.

Olgac, N & Wood, M, (1987), **Optimal Trajectory Control of a Robotic Vehicle**, Proceedings of SPIE - The International Society for Optical Engineering, Vol.727, p.282-289.

Petriu, E M, (1991), **Automatic Guided Vehicle with absolute encoded guide-path**, IEEE Transactions on Robotics and Automation, Vol.7, No 4, 562-5.

Petriu, E M & Basran, J S, (1989), **On the position measurement of automated guided vehicles using pseudo-random encoding**, IEEE Transactions on Instrumentation and Measurement, Vol.38, No.3, p.799-803.

Pomeroy, S C, Williams, H R & Blanchfield, P, (1991), **Evaluation of ultrasonic inspection an imaging systems for robotics using TLM modelling**, Robotica, Vol.9, p.283-90.

Premi, S K & Besant, C B, (1983), **A review of various vehicle guidance techniques that can be used by mobile robots of AGVs.** Proc. 2nd Int.Conf. on AGV Systems, p.195-209, IFS Publications, Bedford, UK.

Rappaport, T S & Seidel, S Y, (1989), **Multipath propagation models for in-building communications**, IEEE Conference Publication, No.315, p.69-74.

Robins, M, (1986), **Free-Ranging Automatic Guided Vehicle System**, Proceedings of International Conference on AGV Systems, London.

Sen, A, Wang, C S, Ristic M & Besant, C B, (1991), **The Imperial College Free-Ranging Automated Guided Vehicle System**, Computer-Aided Production Engineering, p.363-372.

Shull, D H, (1986), **Computer Integrated Manufacturing**, Session Papers - American Mining Congress Coal Convention.

Siemens, (1988) **Siemens Components Service**, Siemens AG, MÜnchen.

Spectratech, (1992), Norwich, Jarrold Printing.

Storjohann, K, Zielke, T, Mallot, H A & von Seelen, W, (1990), **Visual obstacle detection for automatically guided vehicles**, Proceedings of the 1990 IEEE International Conference on Robotics and Automation, p.761-766.

Towers, T D, (1985), **Towers' International Transistor Selector**, 1st edition, Delhi, B.P.B. Publications.

Turpin, D R, (1986), **Inertial Guidance: Is it a Viable Guidance System for AGVS?**, Proceedings of the 4th International Conference on Automated Guided Vehicle Systems: AGVS-4, p.301-320.

Van der Horst, W, (1987), **Digital Motor Driver for R/C models**, Elector, 12:56-61.

Voskiakos, G C & Malis, A G, (1990), **Automated guided vehicle system design for FMS applications**, International Journal of Machine Tools and Manufacture, Vol.30, No.1, p. 85-97.

Watson, J, (1983), **Mastering Electronics**, Macmillan Educator, London.

APPENDIX I

APPENDIX I

A.1 A.G.V. Hardware Description

An apparatus description is detailed in order to form a basic understanding of the working platform utilised in this research application.

A.1.1 Vehicle Layout

The research laboratory autonomous AGV is a rectangular vehicle with dimensions 98 centimetres by 58 centimetres and has a mass of 64 kilograms. Four independently driven wheels are placed 25 centimetres from each corner. These wheels are omni-directional based on the Mecanum movement principle and measure 14 centimetres in diameter (Dillman et al., 1988). The wheel structure allows the vehicle to travel in any direction specified by the user. This is accomplished by varying the motor speeds and motor directions for each wheel independently. Each wheel has an independent suspension, preventing the transfer of excess stress to the vehicle due to rough terrain. They are each driven with a 12 Volt d.c. motor through a 1:5 gear ratio. Each motor delivers a maximum of one newton metre when drawing 2.5 ampere. A top speed of 70 rpm is attained from each motor resulting in a linear vehicle speed of 10 centimetres per second. The motors are driven via a d.c. mosfet chopper module. The power requirements of the vehicle are satisfied with two onboard batteries. The vehicle layout is show below.

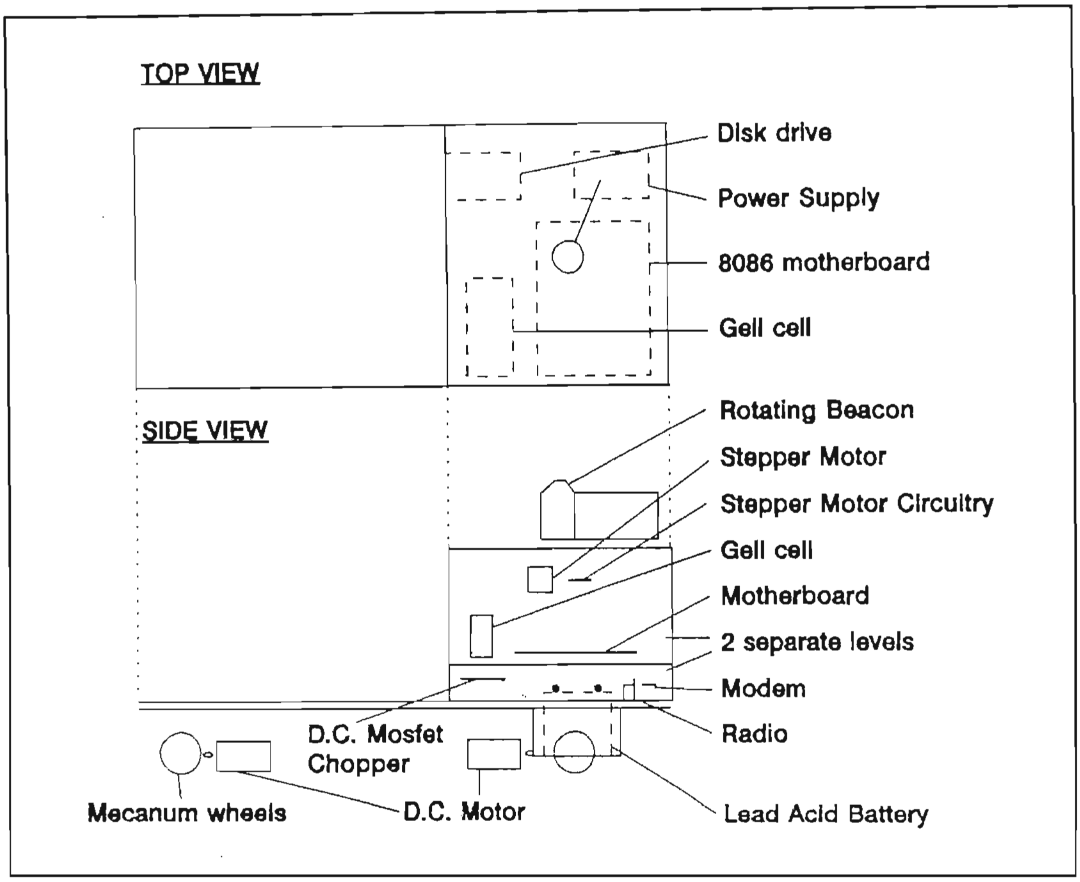
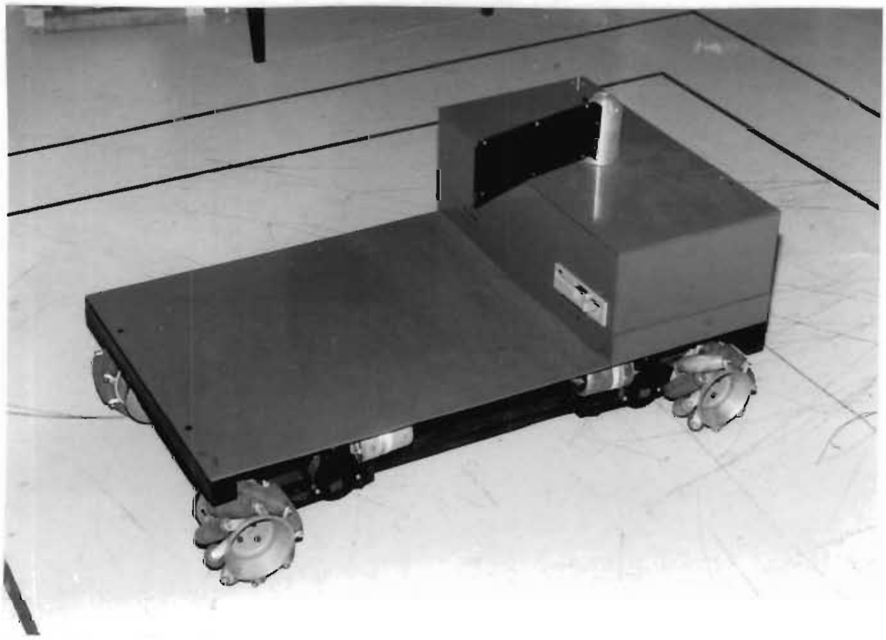


Figure A1-1: Vehicle layout



Photograph A1-1: Side View of Vehicle

A.1.2 The Onboard Power Supply

The onboard power supply consists of a 12 volt 60 ampere-hour lead acid battery and a 12 volt 6,5 ampere-hour gell cell battery. The positive terminal of the gell cell is coupled to the negative terminal of the lead acid battery and this forms a centre ground rail. The negative of the gell cell produces a negative 12 volt rail with respect to the vehicle ground and the positive of the lead acid produces a positive 12 volt rail. These supplies are input into voltage regulator circuitry to produce a resultant power supply of ± 12 volts and ± 5 volts (see figure A1-2). The onboard power is used to drive a vehicle motherboard, modem, transceiver, mosfet motor driver and navigational equipment, including a stepper motor and infrared transmitter.

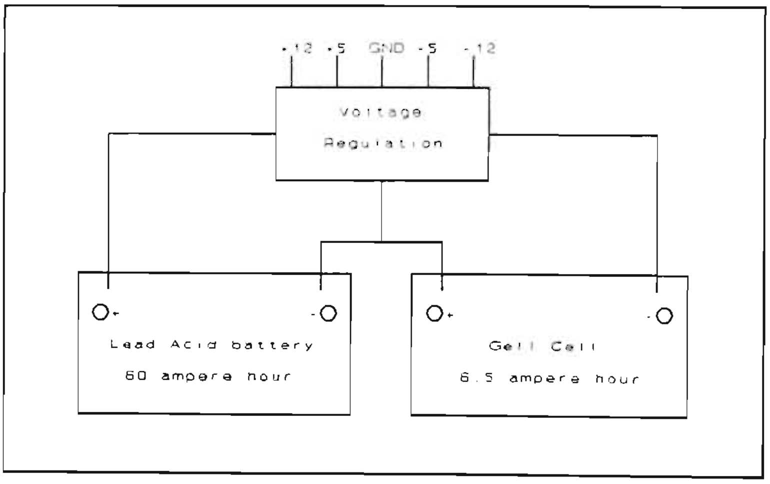


Figure A1-2: Block Diagram of Power Supply and Distribution

A.1.3 The Power Supply Board

The 12 volt rails are supplied directly from the batteries but do have 2200 μF and 0.1 μF smoothing capacitors. The positive 5 volt reference is achieved using a low power 5 volt regulator and this biases a power transistor (TIP127) to supply 5 volts at a maximum of 5 ampere (Towers, 1985).

The negative 5 volt supply uses minimal current (less than 100 milliampere) and therefore a low power negative 5 volt regulator is used supplying a maximum of 100 milliampere. These outputs satisfy all the vehicle onboard power requirements. A schematic diagram of this regulation is shown below.

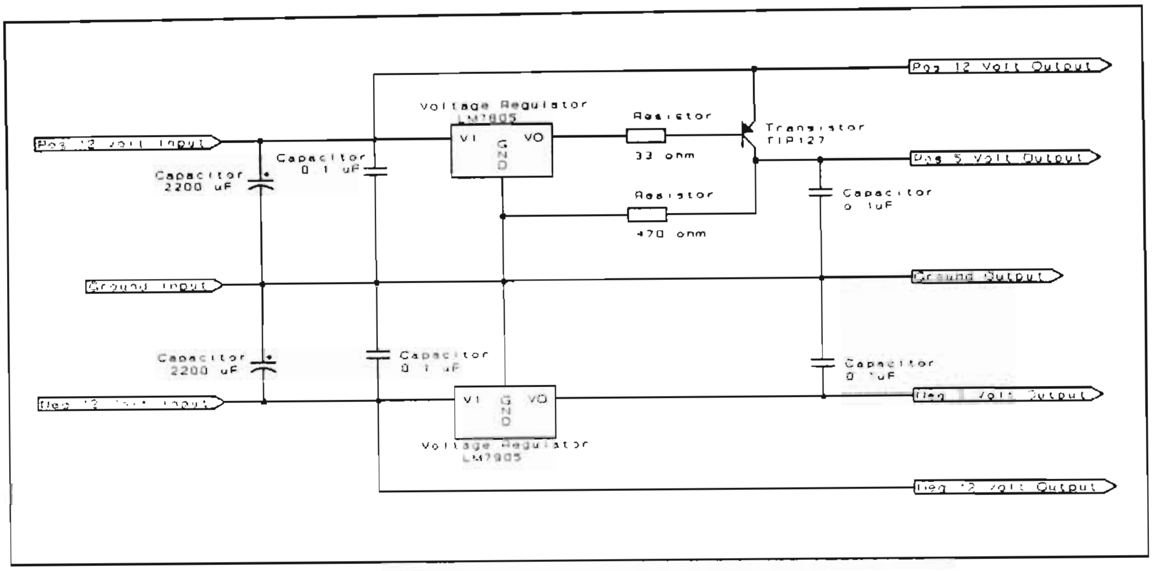


Figure A1-3: Schematic Diagram of voltage regulator

A.1.4 The Transceiver and Modem

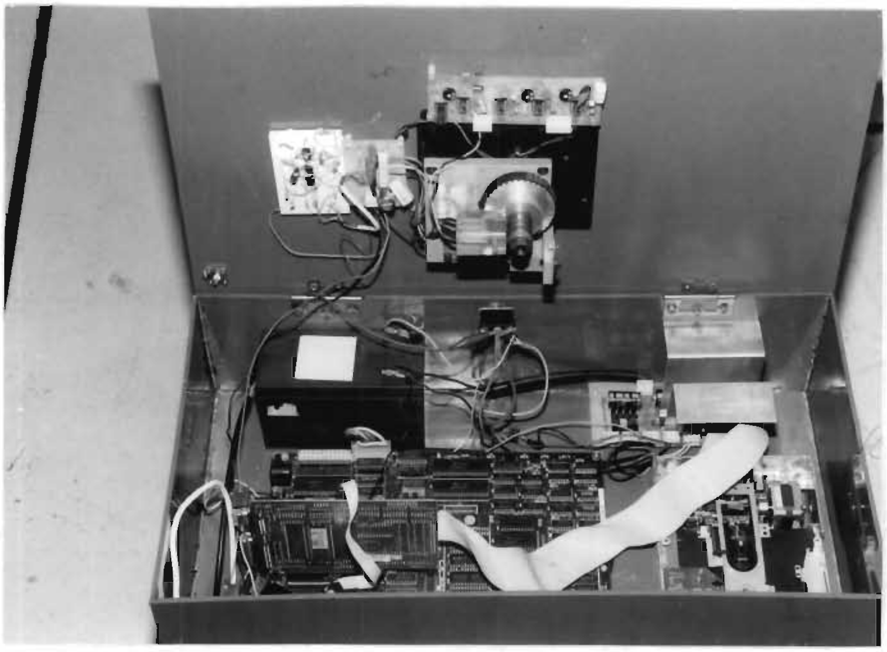
For communication between AGV and the controlling landbase a radio link is used. Both the radio and modem are located in the main battery compartment, this is to minimise radio interference with the motherboard (see figure A1-1). A Faraday Cage is achieved by placing aluminum foil inside the electronics compartment. The radio medium used is a frequency modulated waveform on a 144 MHz band. This frequency could be harmful to microprocessors if no Faraday Cage is used to protect the processor electronics. The radio operates on 5 volts and uses a maximum of a 100 milliampere, which is supplied from the positive 5 volt rail. The interface between the radio and the motherboard is accomplished using a modem and is designed with a baud rate of 300 and communicates using the motherboard RS-232C interface. The modem operates on 12 volts with a negligible power consumption (less than 20 milliampere) and this power is obtained from the positive 12 volt rail. Further supply voltage smoothing is performed on the modem board to minimize problems occurring due to interference. Communication is covered in chapter two.

A.1.5 The Navigational Equipment

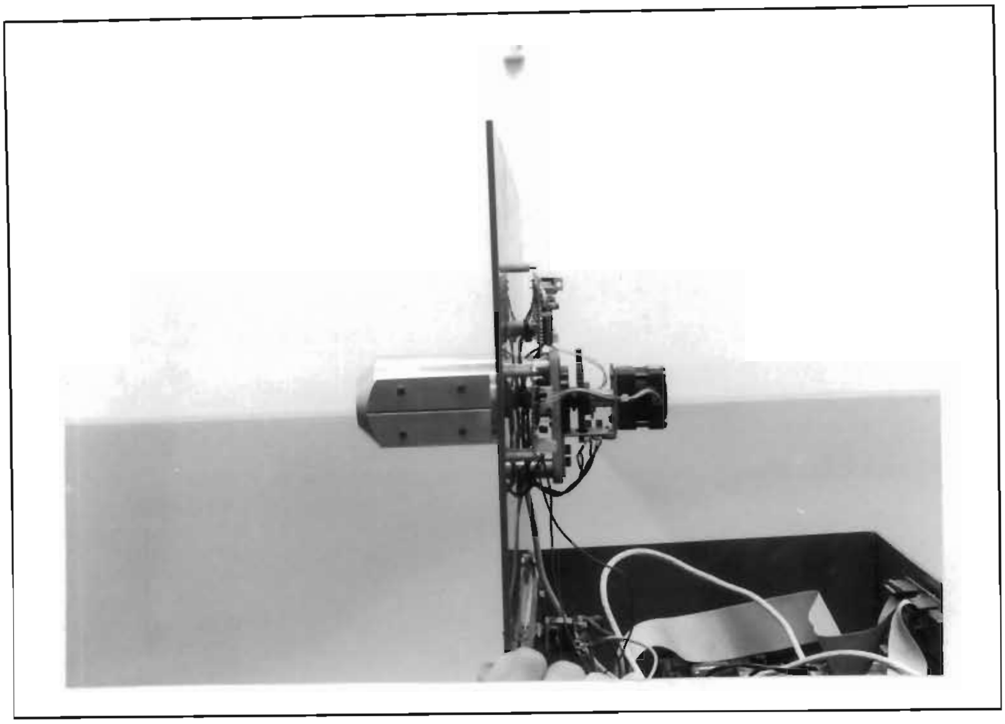
A stepper motor and infrared electronic circuitry are the main components used in the navigation. Onboard the vehicle the navigational equipment is located on the upper lid of the electronics housing, this is the highest point of the vehicle and consequently is used as a viewing platform (see figure A1-1). The stepper motor turns a rotating housing while the microprocessor monitors its rotational position. Navigational information is interfaced both with the motherboard and the landbase computer. The navigation is covered in detail in chapter four and five.

A.1.6 The Vehicle Motherboard

The onboard motherboard uses an 8086 microprocessor and 640 kilobytes of random access memory (RAM). It requires a +5 Volt 1 ampere supply for the motherboard to function. The communications port, which is RS-232C, requires a positive voltage between +6 volts and +15 volts and a negative voltage between -6 volts and -15 volts (Leibson, 1989). Four output ports from an 8255 interface chip drive the navigation stepper motor, another four of these ports determine the direction of the four d.c. motors that drive the vehicle and one other drives a request to send (RTS) signal for radio communication. Another output port determines whether the motor should be on or off. An interrupt vector is utilised for incoming radio communication signals and four others were used in the initial navigation system. The program storage is achieved using magnetic media. When the motherboard is powered up the magnetic media is automatically accessed and the program loaded into RAM and executed. This program has overall control of the vehicle monitoring and all the input and output parameters.



Photograph A1-2: Photograph of Main Electronics Housing Onboard AGV



Photograph A1-3: Photograph of Onboard Navigation System

A.2.1 Design and Construction of the Modem

The FSK tone generation is achieved using an Exar XR-2206 function generator integrated circuit. This is dedicated to FSK modulation and offers attractive features for use in radio medium modulation. The sinusoidal output waveform has a total harmonic distortion of no more than 2.5 percent. This means that rapid output voltage changes originating from many modulator integrated circuits can cause frequency harmonics on the carrier medium and this results in sporadic errors when demodulating the signal. Due to the sinusoidal nature of the output waveform the harmonic interference is kept to a minimum (Exar Integrated Systems, 1978). The circuitry offers excellent temperature stability and is almost free of voltage dependent drift or distortion. These are appealing features in AGV applications where d.c. motors and their associated chopper power management techniques can cause severe power rail distortion. The tone generator is configured to output a low frequency of 1070 Hz for a low input binary signal from the computer and a high frequency of 1270 Hz for a high input binary signal from the computer. The schematic diagram applied to the XR-2206 is shown below. The data input is applied to pin 9. A high level input selects the high frequency (f_h = 1/R1C1 Hz) and a low input level selects the lower frequency (f_l = 1/R2C1 Hz).

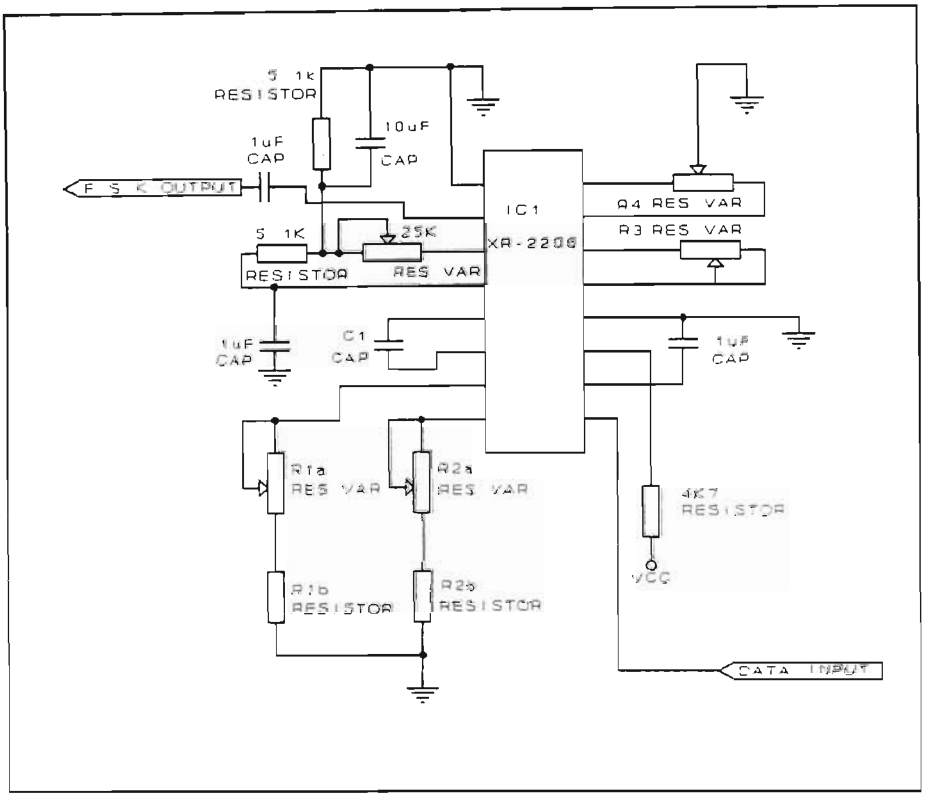


Figure A1-4: Schematic of XR-2206 Modulator used in FSK Modem

The FSK demodulation is achieved using an Exar XR-2211 demodulator. This operates on the phase-locked-loop principle. The centre frequency (f_o), which falls midway between the high and low frequency, is determined by the formula: f_o = (1/R1C1). The tracking range is the scope of frequencies over which the phase-locked-loop can retain lock with a varying input signal. This is determined by the formula: Δf = (R1*f_o/R2). The capture range is the range of frequencies over which the phase-locked-loop can acquire lock. It is always less than the tracking range. The capture range is limited by C2, which, in conjunction with R5, form the loop filter time constant. The damping factor (τ) determines the amount of overshoot or undershoot available in the phase-locked-loop when there is a change in frequency. It is determined by $\tau = \frac{1}{4}(C1/C2)^{\frac{1}{2}}$. It is recommended to choose $\tau \approx \frac{1}{2}$. τ_f is a filter time constant that removes chatter. τ_f is approximately equal to (0.3/(baud rate)) seconds ($\tau_f = R_f C_f$). The lock-detect filter capacitor removes chatter from the locked-detect output. This output is connected to the modems respective motherboard interrupt to suspend the normal workings of the program and manage the incoming data. When this is activated the microprocessor executes a subroutine which receives the incoming data from the modem. With Rd = 510k, the minimum value of capacitance (Cd) can be determined by: Cd (μf) $\approx$ 16/capture range in Hz (Exar Integrated Systems, 1978). The schematic diagram applied to the XR-2211 is shown below.

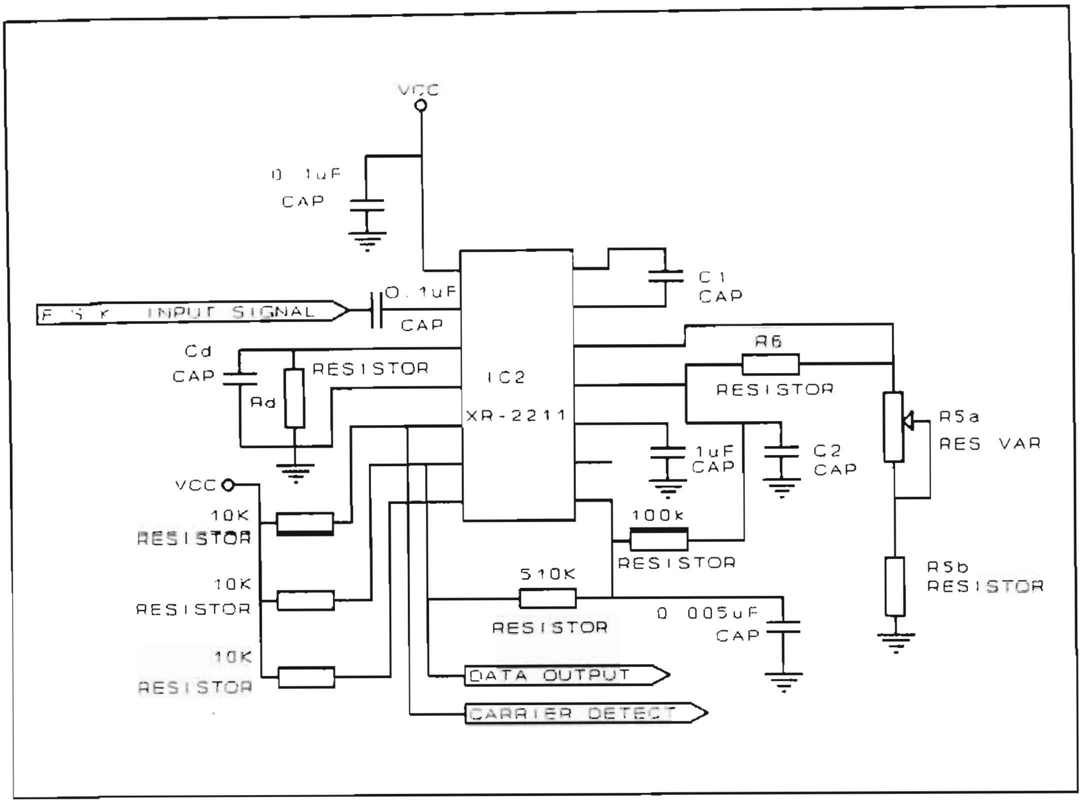


Figure A1-5: Diagram of XR-2211 Demodulator used in FSK modem

The AGV's motherboard and the CAP's computer have standard RS-232C interface ports. These communication signal lines range from positive 12 volts to negative 12 volts. To interface these outputs voltages levels with the modem, a Maxim interface integrated circuit (MAX-232) is used. This converts the outputs from the RS-232C communication ports to standard 5 volt T.T.L. logic levels compatible with the modem (Maxim Integrated Products, 1989). A schematic diagram representing the input and output voltages for the MAX-232 is given below.

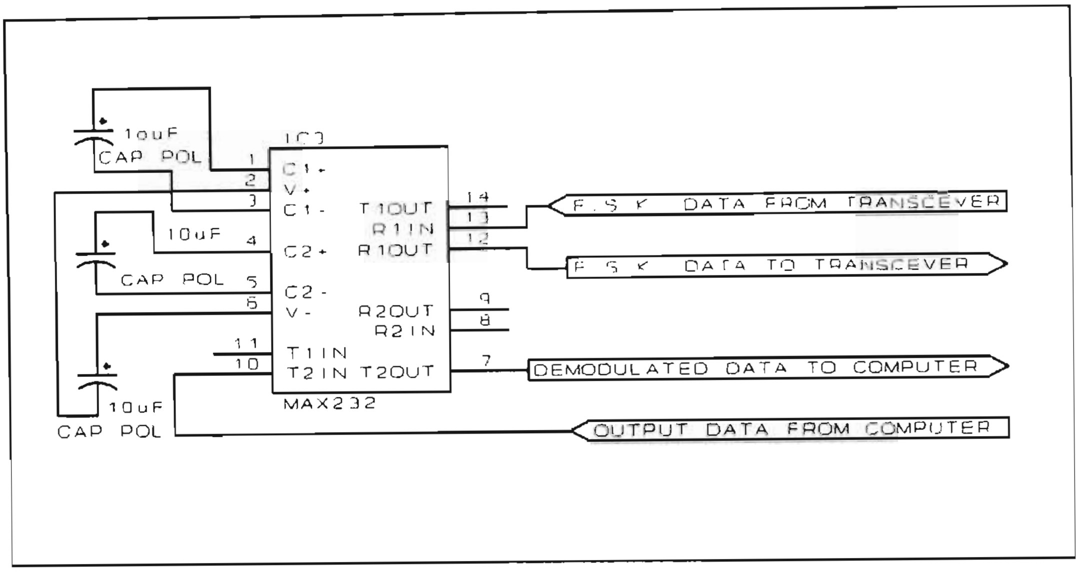


Figure A1-6: Schematic Diagram of MAX-232

Using the above mentioned three integrated circuits a simple modem design is presented.

A.2.2 Communication Hardware Testing

The two modems require calibration and testing. The following procedure was implemented for modem adjustment: The frequencies corresponding to a high and low signal were adjusted on the XR-2206 frequency modulator. The data input (pin 9) was connected to the 12 volt supply rail and the sinusoidal output (pin 2) monitored. By adjusting the potentiometer (R1a) the high frequency output was set. The data input (pin 9) was then connected to the ground voltage rail and the sinusoidal output (pin 2) again monitored. This low frequency calibration was achieved by adjusting the potentiometer (R2a). When connecting the data input to the 12 volt supply rail the output frequency was measured and set to 1270 Hz. In the same manner, when connecting the input to the ground voltage rail the output frequency was measured and set to 1070 Hz. A further advantage of this modulator integrated circuit lies in the fact that both sinusoidal FSK output frequency settings were found to be independent of each other.

The XR-2211 demodulator required tuning of the centre frequency. Before any frequency tuning could occur it was necessary to stabilise the voltage controller oscillator output. This is because the loop-phase-detector output voltage is essentially undefined and the sweep frequency (the waveform that searches for a comparable input frequency) is undefined and varying. To fix this sweep frequency equal to the centre frequency, pin 2 and pin 10 had to be short circuited and the centre frequency measured at pin 3 with Cd disconnected. The centre frequency was then adjusted using the potentiometer R6a and monitoring the frequency output at pin 2. This frequency was adjusted to 1170 Hz. Having accomplished these settings, verification of the functionality was achieved in the following manner.

The output of the modulator (pin 2 of the XR-2207) was connected to the input of the demodulator (pin 2 of the XR-2211). A pulse train of 300 Hz was supplied to the input of the modulator (pin 9) at a frequency of 300 Hz and the output of the demodulator (pin 7 of XR-2211) was monitored on an oscilloscope. This pulse train input is equivalent to a communications port baud rate of 300. The oscilloscope waveform was monitored and the potentiometer R6a was finely tuned, eliminating chatter on the output waveform.

Once the above modem testing proved to be successful it was necessary to establish a direct communication link between the two motherboards. This process was instituted to verify the functionality of the communication subroutines and hardware wiring between the two RS-232C communication ports. It should be understood that the use of the modems is required only for voice synthesis necessary for the radio medium communication. It is therefore unnecessary when direct wire communication between two motherboards is required (See Appendix III). This wire communication testing was achieved by coupling the two communication outputs from each motherboard together. Both motherboards have standard 25 pin 'D-type' connections and these have predefined standard RS-232C output pin configurations. The transmit data (pin 2) of each motherboard output is connected to the respective recipient receiver data input pin (pin 3). The ground lines of each motherboard are directly coupled together. These three lines are sufficient for bidirectional communication between the two motherboards provided there is only one talker at a time. All the other lines of the RS-232C 'D-type' connector, apart from two unassigned lines, are control wires and are used to establish and maintain the communication link. It should be noted that RS-232C was initially designed for interconnection between data communication equipment (DCE) and data terminal equipment (DTE). This host and recipient configuration does not usually occur with two intelligent motherboards requiring duplex communication. However, each motherboard takes a turn to send and receive data and therefore the sender can be considered as the DTE and the receiver as the DCE. A diagram of the wiring configuration is shown in figure A1-7.

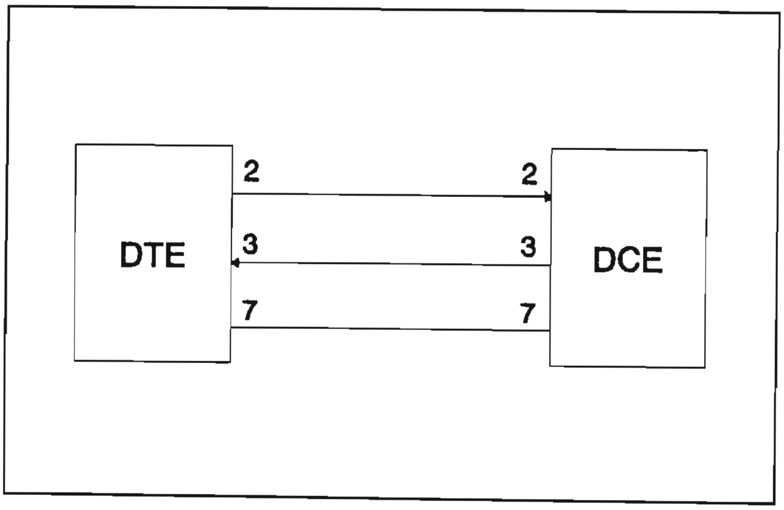


Figure A1-7: Minimum RS-232C Connections for Duplex Operation

A 5 metre cable comprised of the above wiring configuration was connected to each of the motherboards. Routines were set up to transmit and receive data on a continuous basis at half second intervals. The check sum algorithm was disabled. This was to allow for interrogation of incoming data without it being discarded. The predefined arrays namely, route data, navigation data and instruction data, were transmitted on a cyclic basis. The route data consisted of five paths comprising a total of 22 data values. The navigation and instruction data each consisted of 4 data values (this is taking into account that no check sum value was submitted). A total of 150 data arrays making up 4500 byte values were passed through this communication link. The values were interrogated and verified against their transmitted values and a 100 percent error free reception for all 4500 bytes was accomplished.

In order to verify the functionality of the modems together with the two motherboards the correct procedure entails direct coupling of the modem to their respective motherboards. The modem FSK outputs were then coupled to their corresponding modem FSK inputs. This eliminated the wireless transceiver link. The outputs of the MAX-232's of each modem were connected to their respective motherboard communication ports. The same data testing routines were then implemented to verify the functionality of the modems. A total of 150 data arrays making up 4500 byte values were passed through this communication link. The values were interrogated and verified against their transmitted values and a 100 percent error free reception for all 4500 bytes was accomplished.

After this procedure the modems were disconnected from each other and linked directly to their respective transceivers. The desired wireless communication link was achieved. The testing procedures are to be detailed in section A.2.7. Each transceiver was connected to a modem and an extra output port from the motherboards was used to operate the 'push-to-talk' signal input. When intending to transmit data this output control signal activates the transceiver. It was found that a 50 millisecond activation signal, prior to transmitting data, was necessary for activation of the receiving modem. This was needed to allow time for the receiving program-interrupt to prepare for the incoming data.

A.2.3 Protocol

In both the transmitting and receiving programs the baud rate, parity and stop bits have to be pre-defined and configured. This is so that the protocol for the transmission byte is the same as that of the reception byte. This configuration is all pre-defined in the initial settings of the main program (Leibson, 1989). On reception of data the modem firstly determines the integrity of the incoming signals. Provided that the incoming tones fall into the predetermined communication values, the modem activates an interrupt of the microprocessor. This interrupt calls a subroutine which performs the task of data integrity checking and verification. One subroutine is used for transmitting data while another is used for receiving data. The communication structure only allows for data transfer in one direction at a time. Before any data transfer can commence the sender station must first ascertain whether the radio frequency medium is unused. This information is established between the microprocessor and modem. Whenever the radio link is unused, data may be transmitted. When not transmitting information, the modem and microprocessor are in receive mode.

When the CAP is controlling and monitoring the AGV, near real-time simulation and surveillance is required. In effect two way communication (duplex communication) between the AGV and CAP is needed at all times so that real-time information is transferred. Real-time information includes data such as path layout, required destination, vehicle interrupt, vehicle position and vehicle status. When the CAP or AGV needs to transmit information a transmission subroutine is called which reads data from an output array. This data is output one byte at a time into the microprocessor output holding register. The byte is then clocked out of the communication port in a serial fashion at a predefined baud rate, parity and stop bit. This pre-defined protocol consists of 8 stop bits, even parity and a baud rate of 300. If the received data does not comply with this protocol a data integrity error is generated.

A.2.4 The Transmitting Subroutine

Before data is transferred a push-to-talk signal must be activated on the transceiver. Activation is accomplished using a motherboard output port. When the program requires data transfer, the push-to-talk is activated from the transmitting subroutine 50 milliseconds prior to transmission. This takes control of the radio transmission line. The subroutine then writes a data byte to an output holding register located at hexadecimal address (&H02F8). The byte is then clocked out to its respective modem through an RS-232C output port using the predefined protocol. Once the byte has been unloaded out of the port, another byte is loaded into this output holding register. This process is continued until all the required data has been clocked out. At the end of each data array, a termination value is placed to confirm the end of transmission. This confirmation is used to terminate the transmitting and receiving subroutines. The clocked output pulses are encoded in the modem into specific FSK tones and superimposed on the radio carrier frequency. A flowchart of this subroutine is given below.

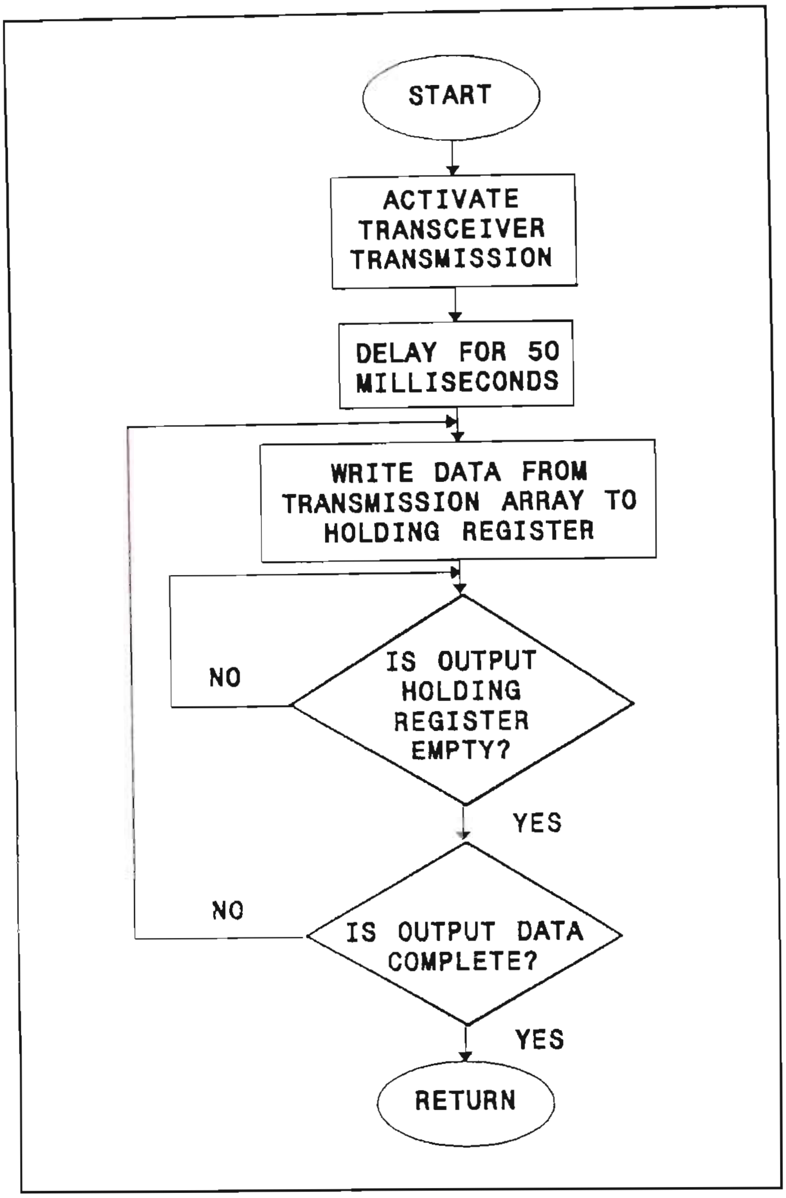


Figure A1-8: Flowchart of Radio Transmission Subroutine

A.2.5 The Receiver Subroutine

A transmitted radio signal is received by the transceiver. This is demodulated from the 144 MHz FM band and input into the modem. The modem firstly must verify that the incoming signal is comprised of predefined FSK tones. If the signals do not consist of these tones, the signal is immediately discarded. Provided the signals are correct, the modem uses the transmitted 50 millisecond initialization signal to halt the normal functions of the receiver program. This is achieved by activating the motherboard interrupt which stops the main program function and prepares the receiver subroutine to service the incoming data. The receiving motherboard will take a maximum of 50 milliseconds to halt any function with which it may previously have been engaged. The FSK tone signals are demodulated by the modem into their respective binary 0's and binary 1's. These are then input into the RS-232C communication port which loads the binary value into the input holding register one byte at a time. A holding register flag is activated when the input holding register contains one full byte. A loop in the receiving subroutine continually checks the holding register flag and when it is activated the holding register value is read into an input array. This incoming data is stored and once the communication signals have terminated, the data is interrogated. All communication data has a leading and trailing information protocol. These values perform two functions. The first function is determined by the leading protocol. This is consisted of two information bytes and informs the receiver station of the composition of the data. The last byte of the incoming data array is a checksum correction value. This byte is a verification of the integrity of the received data. A final integrity checking is accomplished by verifying the incoming data prior to it being passed on to any of the subroutines. This verification observes a standard checksum procedure and is used to verify the integrity of the data. This procedure adds all the requested transmitted data together before transmission (the checksum value is chosen to be multiples of 128). This data is then subtracted from the closest multiple of 128, the remainder being the last transmitted value. This procedure is carried out prior to transmission of the data. The data is then transmitted in its original form. The received data is first stored in its original form. All the values of the array are added together including the last value. This total should again make up a value of a multiple of 128. If the total received array value is not a multiple of 128 then all the data is discarded and a retransmission is requested. It is assumed that if the last incoming byte of the array has the correct incoming value then a high probability exists that all the preceding transmitted values are correct. This assumption is made because, in the event an incorrect received value, the checksum would result in a checksum error value. This checksum integrity checking proved sufficient for this short range wireless communication. During system testing 2500 bytes were transmitted with no invalid data reception. Further detail is given in the section on communication testing and results. It should be noted here that many advanced data integrity checking procedures exist, one being 'packet-radio' but it was considered unnecessary in this application as the checksum method resulted in 100 percent transmission. The integrity and value of the input information determines whether the data is sent to various subroutines or whether it is to be discarded. It is now necessary to detail the procedures for directing the received data array to the appropriate subroutine.

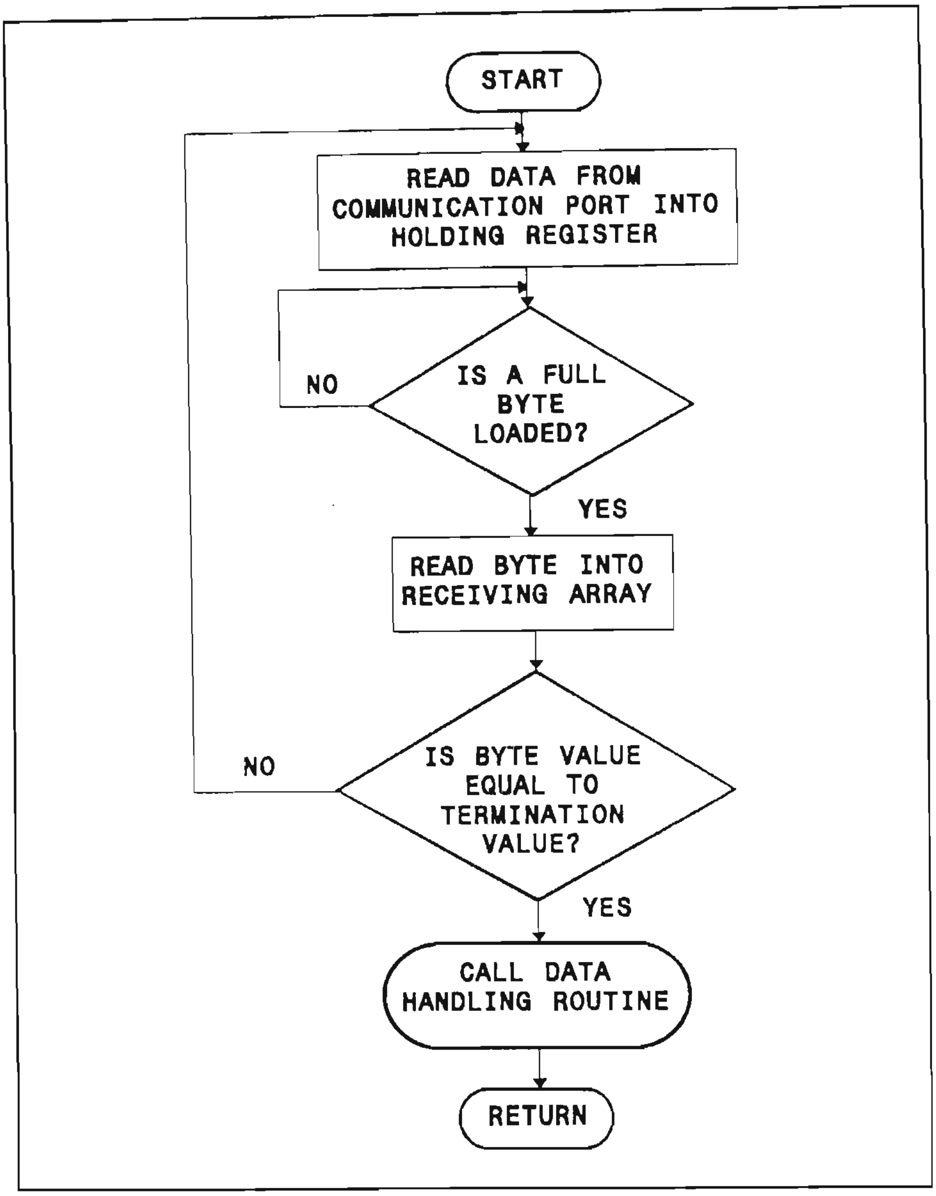


Figure A1-9: Flowchart of Radio Receiver Subroutine

A.2.6 Receiving Array Command Protocol

All data is transferred in numerical form. The leading two values received are numerically interrogated and have specific functions. The first value defines whether the data has been transmitted previously. If the first incoming byte corresponds to the value of 127 then a first pass transmission is assumed. However, if the first incoming byte corresponds to a value of 126 then a second pass transmission is assumed. The second value received corresponds to the category of incoming data. These three categories constitute the communication definition structure. These are navigational data, route structure and commands or requests.

a) Navigational Points

The second incoming byte value is numerically evaluated. If this value is found to be numerically equal to 126 then the preceding pair of numbers is assumed to correspond to a navigational point. This is only provided that the final value agrees with the integrity checking procedure then the two navigational values are transferred to a guidance subroutine algorithm.

b) Route Definition

If the second received incoming numerical value is 125, then all preceding data, apart from the last numerical value, is assumed to correspond to a route definition array. Provided the final value agrees with the integrity checking procedure then the data is sent to a route definition array. A sorting algorithm determines the beginning and end point of the path structure. The algorithm then interconnects all the corresponding intermediate path nodes. These points constitute the path layout and are used in the guidance subroutine.

c) Request Definition

If the second received incoming numerical value is 124, then the preceding two values, apart from the last numerical value, is assumed to correspond to a request definition. Provided the final value agrees with the integrity checking procedure then the data is sent to a request definition subroutine. The data is then interpreted and categorized into request definitions as follows. If the third incoming value is numerically equal to 1 then a request for resubmission of previously transmitted data is submitted. If the third incoming value is numerically equal to 2 then a control command is issued to stop the AGV immediately. If the third incoming value is numerically equal to 3 then a control command instructs the AGV to return to its base station. In this manner, a large command structure can be generated to cover all the needs of an autonomous AGV.

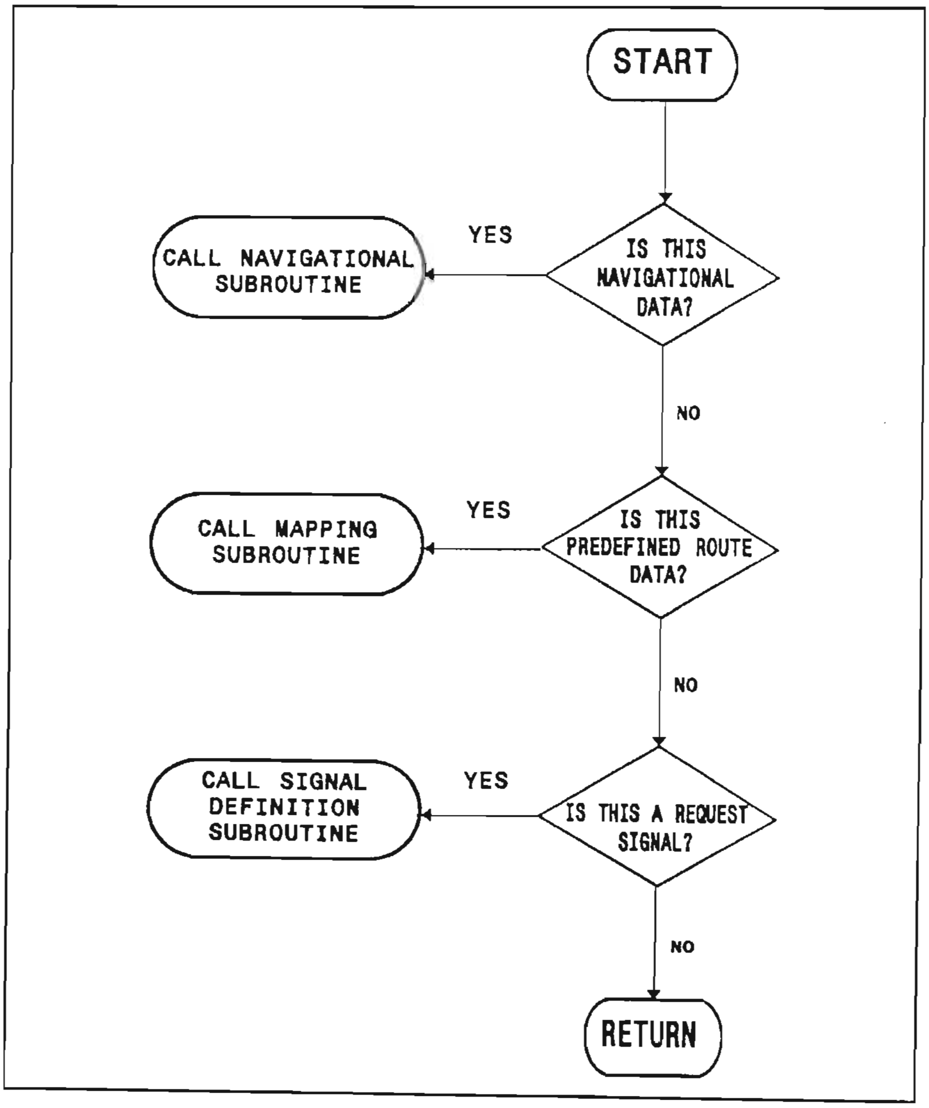


Figure A1-10: A Subroutine Flowchart for Incoming Data array Supervision.

A.2.7 System Testing

Once the communication system was fully implemented, a number of tests were carried out. These were aimed at verifying the functionality of the wireless system in conditions similar to those of a manufacturing environment. The tests conducted were system range in direct line of sight, system range with obstacles such as a machine and other large metal objects, functionality of the system through concrete partitions and functionality of the system when subject to interference.

Test 1

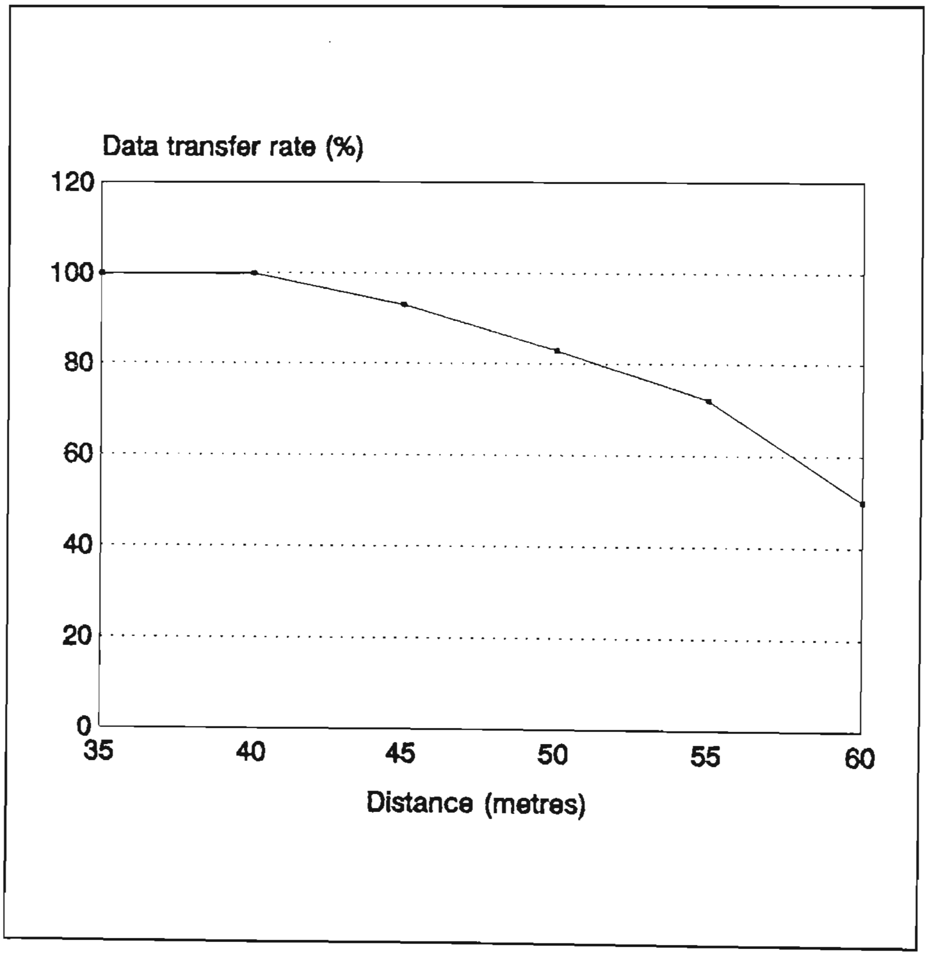
A direct line of sight transmission was firstly carried out to determine the effectiveness of the wireless communication with regard to distance. The CAP and AGV were placed in an empty parking lot and test data was transferred over various distances. Because it was impractical to locate a terminal onboard the AGV, a functional command was implemented to verify the arrival of the data at the AGV. This functional implementation was merely to start and stop the AGV motors. Once the command was received an acknowledgement was returned to the CAP. In this manner, a verification of each transmitted data signal was achieved. Five hundred data bytes were transferred at 1 second intervals over a distance of 100 metres, 200 metres, 300 metres and 400 metres. 100 percent error free transfer was obtained. It was considered beyond the scope of this research to attempt to achieve a greater range. Having accomplished this, it was decided to implement a more practical communication test with regard to AGVs in their manufacturing environment.

Test 2

One major advantage of VHF FM wireless communication is that it has the ability to communicate around objects or machines. It is for this reason that it was deemed necessary to verify this advantage with the communication system built and implemented in this research project. The vehicle was placed in a simulated manufacturing environment and instructed to move around a lathe, milling machine and workbench. During this manoeuvre continuous communication between CAP and the AGV was achieved with 100 percent error free data transfer. The CAP transmitter was no more than a maximum of 20 metres from the AGV at any time during this operation. However, most of this data transfer was not in direct line of sight, but obstructed by the aforementioned objects. One hundred data bytes were transferred between the CAP and AGV during this test.

Test 3

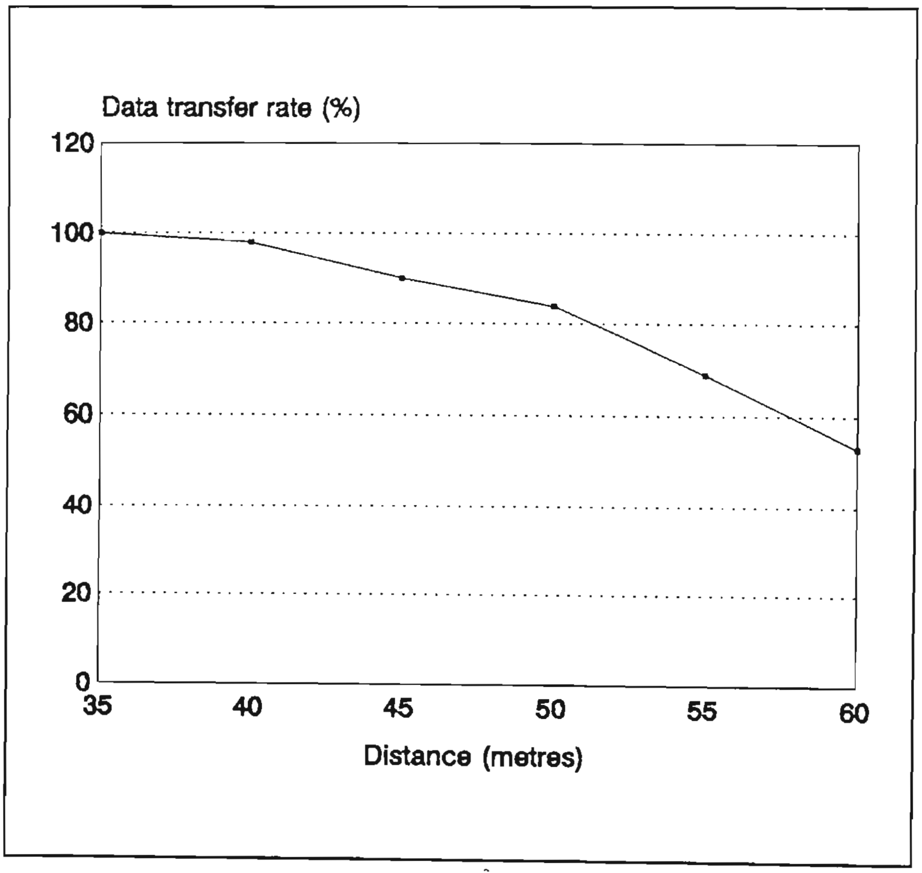
A major function of AGVs in a manufacturing environment is considered to be materials handling and transportation and it is possible that these functions could occur in more than one enclosed area. For this reason it was clearly necessary to verify the functionality of the system when the vehicle was operating in a different room, partition or enclosure to the CAP. Furthermore, it was also considered that this testing was an integral part of developing duplex communication for an AGV system. The vehicle was placed in a separate laboratory, 40 metres away from the CAP. Two adjoining laboratories separated the two communicating transceivers. A total of three, 30 centimetre walls inhibited the transmission signals. One hundred byte values were transferred resulting in a 100 percent error free data transmission. In this test it was observed that although error free data transmission was achieved, some re-transmission requests were submitted. It was concluded that these concrete obstructions largely reduced the transmission range. This resulted in a series of tests to determine the percentage of first pass data transfer acceptance against distance. The checksum error checking was disabled allowing for interrogation of first pass data. To accomplish these series of tests the vehicle was placed at distances ranging from 35 metres to 60 metres at intervals of 5 metres. The percentage data transfer was plotted against these distances. One hundred data bytes were transferred at 5 metre intervals. The graph below depicts that the data transfer rate falls rapidly with distance when the FM communication is required to transfer data through solid concrete boundaries. This phenomenon is detailed in the discussion.



Graph A1-1: Graphical Representation of Percentage Data Transfer Rate against Distance.

Test 4

Given the nature of a manufacturing environment and considering that free-ranging AGVs require wireless communication, it was necessary to test the communication link within this environment. When testing this communication link in direct line of sight (up to 30 metres) within a manufacturing environment, 100 percent error free data transfer was observed. It was decided that these tests were suitable for wireless data transfer within a manufacturing environment. Yet, a further test was conducted to investigate the limitations of the system. The vehicle was again placed at distances varying from 35 metres to 60 metres and a communication link was separated by two adjoining laboratories. The milling machine and lathe were put into operation, and the transmission transfer rate against distance plotted. Comparing the results obtained when the machines were either operational or non-operational, it was clear that no interference was incurred.



Graph A1-2: Graphical Representation of Percentage Data Transfer Rate against Distance when Influenced by Working machinery.

A.3.1 The Mosfet Chopper Module

Direct current motor control was achieved by varying the power to a d.c. motor. This was accomplished by either varying the constant analog supply voltage or the average current to the motor. The former method of motor control was not recommended for free-ranging vehicles because, at reduced motor speeds, excess power was dissipated in the form of heat.

The mosfet chopper module utilised the concept of varying the average power supplied to the motors whilst not sacrificing excess power in the form of heat (Freeman, 1979). The amount of power delivered to each motor was controlled by altering the mark space ratio of the chopper output frequency that drove each motor. This is commonly known as pulse width modulation. It is the more favoured technique for d.c. motor control and is commonly implemented in free-ranging AGV's because there is no power wastage. The method of pulse width modulation d.c. power control can achieve a high efficiency. An efficiency of up to 99 percent can be achieved if fast, high efficiency mosfets are used (Van der Horst, 1987). This resulted in a minimal amount of power being expended as heat, allowing for a significantly longer battery life. In effect this increased the working time of each vehicle battery.

Power is controlled by furnishing short pulse bursts to the motor at a high frequency. The frequency chosen was dependent on the magnetic breakdown characteristics of the motor and therefore each type of motor using this concept should be tested independently. This evaluation can be achieved by increasing the frequency of the chopped d.c waveform and then monitoring on an oscilloscope the reactance caused by the magnetic field (Koff, 1985). Most d.c. motors operate at a chopper frequency of 15 kHz. This frequency was tested on the d.c. motors chosen for this application and the magnetic field characteristics monitored on an oscilloscope.

It was observed when applying this frequency of 15 kHz the pulse width modulated supply voltage tended to breakdown as a result of the reactance of the motor. An 18 khz chopper frequency was applied to overcome this problem.

An LM566 voltage to frequency integrated circuit was used to generate a sawtooth waveform with an output frequency of 18 kHz. An analog reference voltage, proportional to a desired motor speed, was supplied by the computer and compared with this sawtooth waveform. The resultant comparator output was an 18 kHz square wave with a mark space ratio proportional to the desired motor speed. The output ratio of high signal to low signal was proportional to the reference voltage supplied by the computer. Output waveforms from the LM566 and the resultant mark space chopper waveforms are shown below for different analog output voltages.

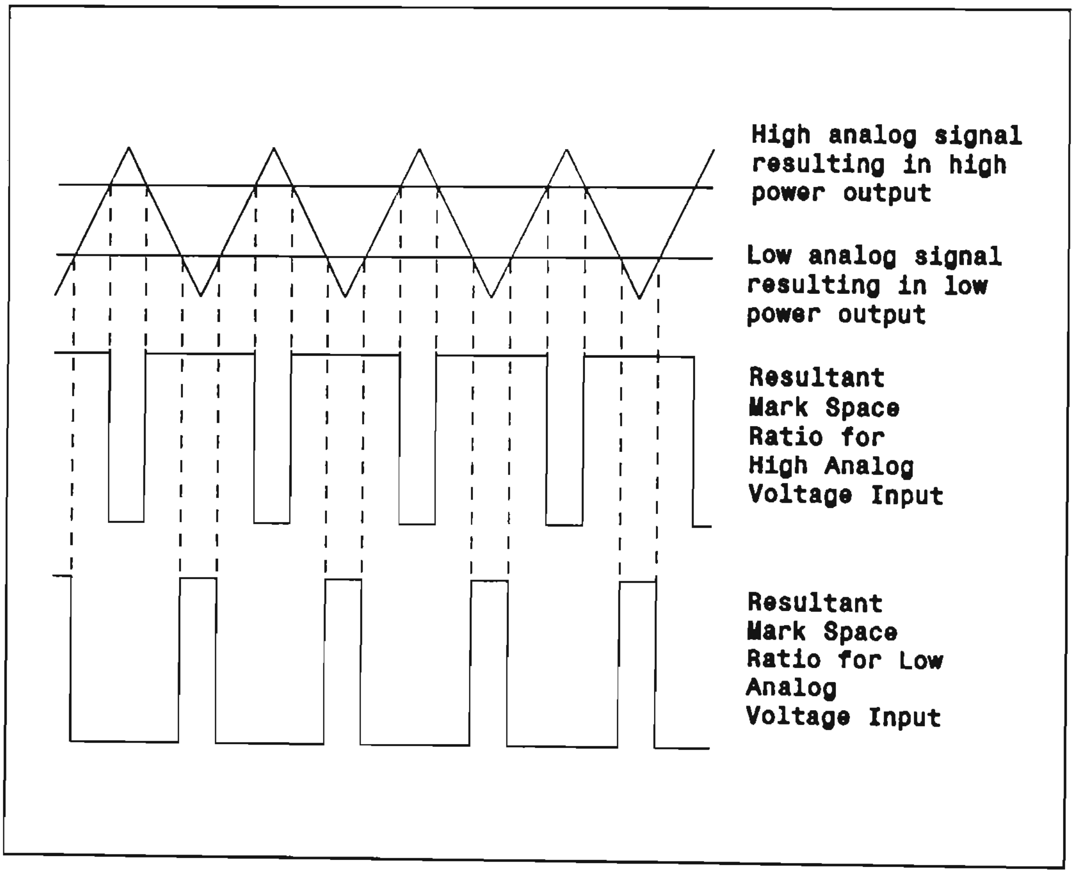
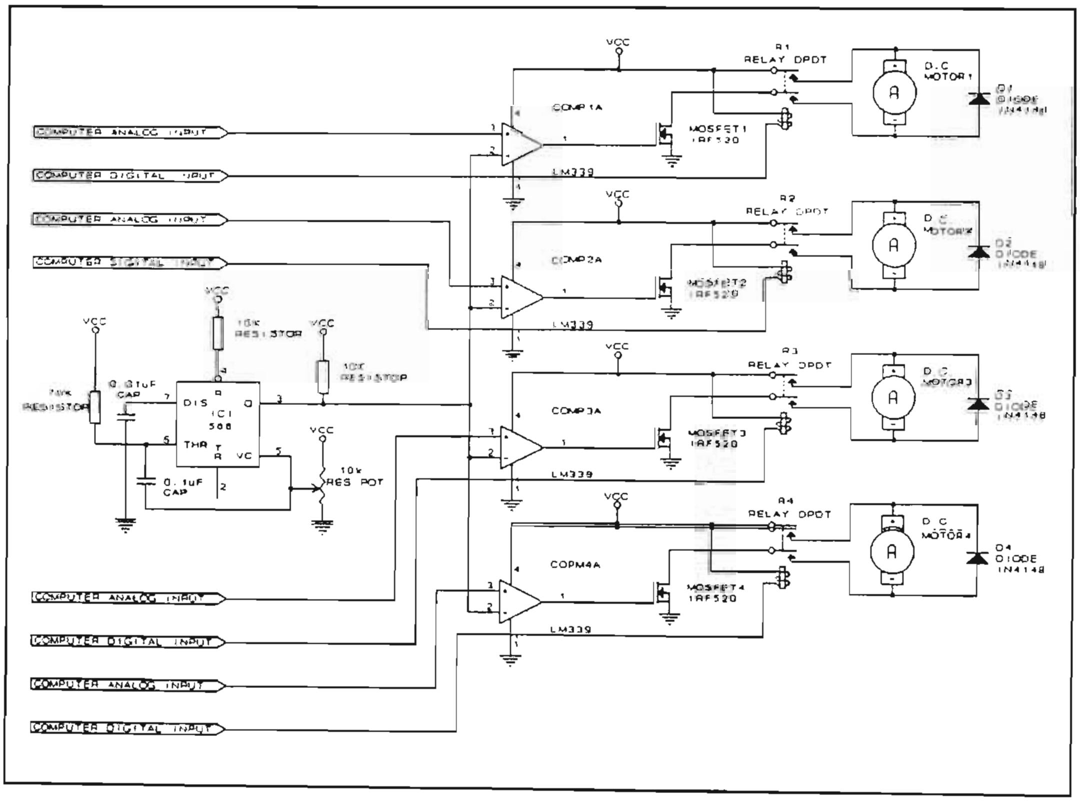
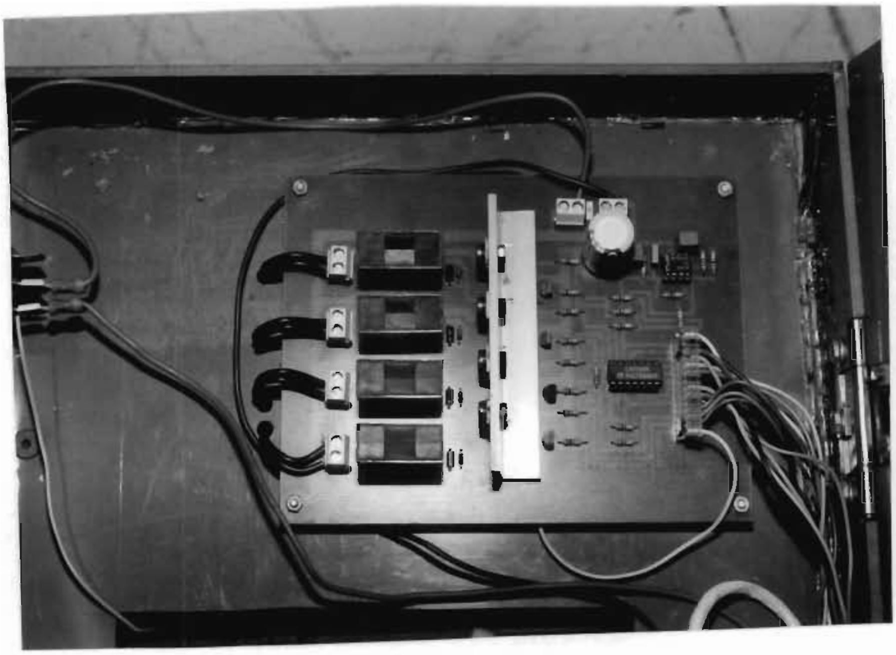


Figure A1-11: Waveform Generated by Mosfet Chopper Module

The square wave controlled a power mosfet (IRF520) and this drove a d.c. motor through a double-pole double-throw relay. The relay coil was controlled from an output port of the motherboard through a switching transistor. Using this configuration, each motor's direction and speed was controlled separately from the computer. This design maintains high efficiency by conserving onboard battery power and satisfies the required Mecanum movement principle. A block diagram for this design is given below, showing the inputs and resultant outputs.



<u>Figure A1-12: Block Diagram Showing d.c. Chopper Configuration</u>



Photograph A1-4: Electronic Chopper Module Circuitry

A.4.1 Path Structuring

A predefined grid reference is established as it is necessary to visually define the location point of two adjoining routes. Using these nodal reference points, path definition is reassigned the closest grid reference node. This allows for the operator to visually determine whether the two path segments are separated or joined at a given node. Without a grid, two path end segments could be infinitely close without physically joining. The grid eliminates this possibility as it would snap these two path end segments onto the grid node.

The path is structured using a digitizer in an interpolative fashion with the CAP computer screen. The path programmer may select this path selection option from the main menu of the controlling program. Upon activation this subroutine requests a starting point from the digitizer. The mapping programmer inputs a starting route location point from the digitizer while simultaneously visually locating this point on the computer screen. This digitized point is converted to the closest predefined Cartesian co-ordinate grid-vector point and stored in a path array. The end point of the route is then digitized and converted to similar predefined co-ordinate points and stored in the same array. This is continued until all the desired routes have been laid. A flowchart of the path description subroutine is presented below.

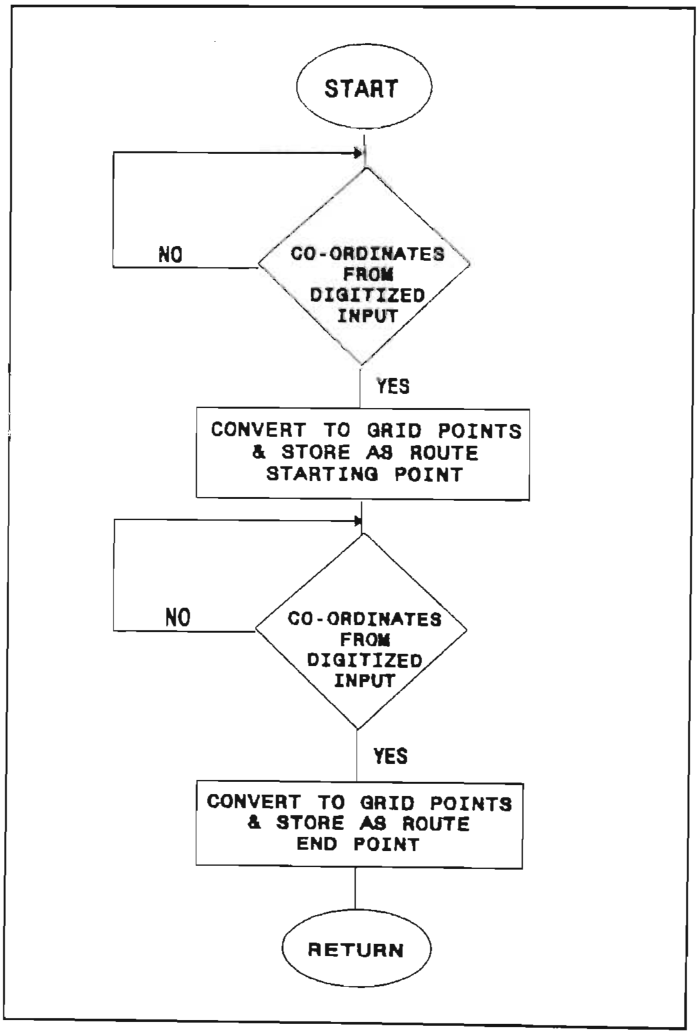
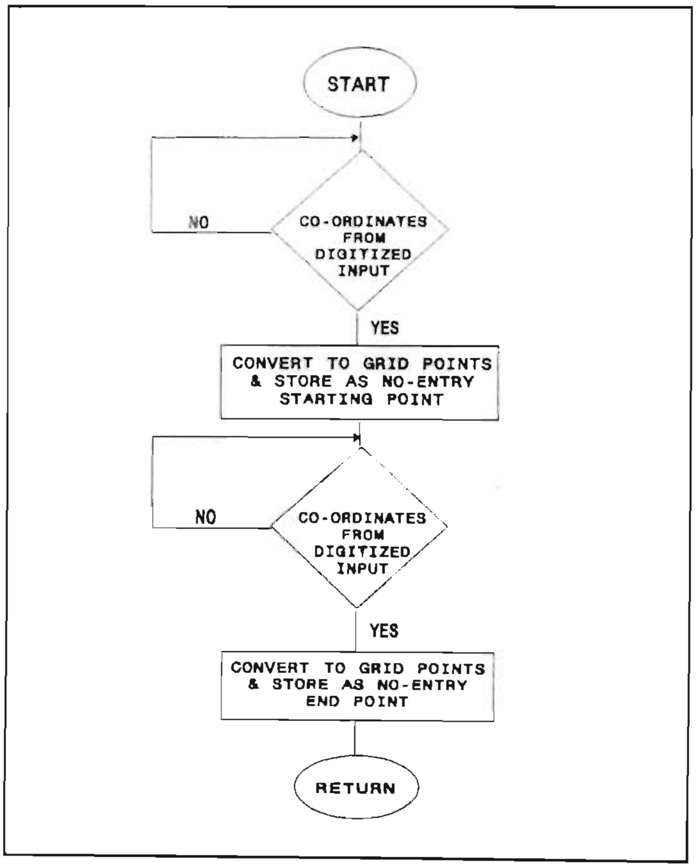


Figure A1-13: Subroutine Flowchart for Route placement

A.4.2 Placement of No-entry Zones

A path programmer may wish to place no-entry zones or areas where the AGV may not physically manoeuvre. This may be an area occupied by a physical obstruction such as a machine or simply an undesired AGV travelling area. The selection of these regions is achieved by the path planning programmer. The obstacle placement selection is accomplished from the main controlling program menu using the digitizer. A subroutine then requests a no-entry zone starting point from the digitizer. The co-ordinates for this starting point are converted to the closest Cartesian grid-vector point and stored in an obstacle array. The opposite end point of the no-entry rectangular array is then input by the path programmer. This digitized point is converted to the closest Cartesian grid-vector point and stored in the obstacle array.



<u>Figure A1-14: Subroutine Flowchart for Placement of No-entry Area</u>

A.4.3 The Delete Option

This option deletes a path or no-entry zone. The selection of these is achieved by the path planning programmer via the digitizer. The delete option can be selected from the main controlling program menu. A subroutine then requests a no-entry zone starting point from the digitizer. If an obstacle or path falls in this requested region it is deleted from the appropriate vector array.

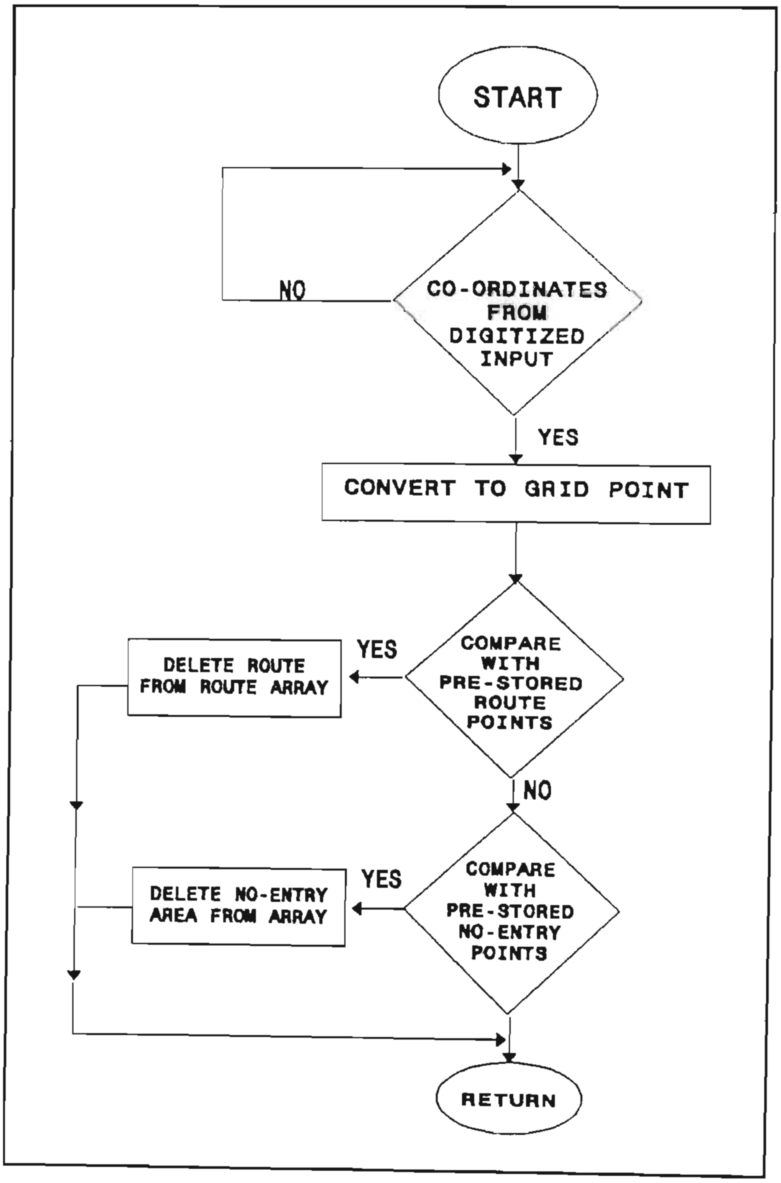


Figure A1-15: Subroutine Flowchart for Deletion of Routes and No-entry Areas

A.4.4 The Map Save Option

Once all the routes and obstacles have been mapped onto the CAP screen this layout can be stored for later use. This map saving menu option saves the path programmer's predefined layout into CAP memory and furthermore, downloads this information via radio link to the AGV motherboard. This section of the program is detailed in Chapter 3.

A.4.5 Real Time CAP Controller

The functionality of the subroutine categorises it within the broader concept of system integration. The functions of real time monitoring do not fall into the category of guidance per se, but nevertheless are briefly discussed to lend a more complete understanding of guidance monitoring. A detailed explanation of real time monitoring is presented in Chapter 3.

A facility of real time AGV monitoring and controlling has been developed for this research application. The functions offered in real time are dispatching of a vehicle, monitoring AGV movement and the option of interrupting the normal workings of a vehicle. This monitoring and control can be accomplished by the operator from the CAP. The real time subroutine plots the positional navigation points of the AGV onto the CAP display monitor. Furthermore, it transmits these navigational points to the AGV for guidance and control. The operator may at any time instruct the vehicle via the keyboard to stop, immediately return to its base station or return to its base station once a task is completed.

A.4.6 The Terminate Program Option

The programmer may desire to abandon the main controlling function. An option is offered in the main menu which allows the operator to abort the main program and return the CAP functions to the main operating system. In this case the main operating system is Disk Operating System (DOS).

APPENDIX II

APPENDIX II

B.1 System 1

Calculations to determine the maximum delay between infrared receiver activator and decoded signal output.

Absolute maximum time for IS 471F decoder to produce output for a given 38 kHz excitation input is:

delay(excitation) = 800 microseconds . . . . Eqn B1

Maximum time for IS 471F infrared decoder to recover from the removal of excitation frequency is:

delay(recovery) = 800 microseconds . . . . Eqn B2

Therefore, the maximum time to produce one period output from the infrared decoder is:

$$\begin{aligned}\text{Period} &= \text{delay(excitation)} + \text{delay(recovery)} \\ &= 800 + 800 \\ &= 1600 \text{ microseconds} \\ &= 1.6 \text{ milliseconds}\end{aligned} \quad \ldots \quad \text{Eqn B3}$$

Maximum input frequency to any of the LM567 decoders is:

$$\begin{aligned}f &= \frac{1}{T} \\ &= \frac{1}{1.6\times10^{-3}} \quad \ldots\ldots\ldots\ldots \quad \text{Eqn B4} \\ &= 625 \text{ Hz}\end{aligned}$$

For a bandwidth comprising 10 percent of the centre frequency, the maximum specified number of pulses to produce an output is 15 cycles.

<u>Beacon 1</u> was chosen to have a superimposed lower frequency of 600 Hz. Therefore, the maximum delay to produce an output from a LM567 with a centre frequency of 600 Hz and a

bandwidth of 60 Hz is:

$$\text{Period for 1 cycle} = \frac{1}{600} \text{ seconds}$$

$$\text{Period for 15 cycles} = \frac{15}{600} \text{ seconds} \qquad \ldots\ldots\ldots \quad \text{Eqn B5}$$

$$= 25 \text{ milliseconds}$$

<u>Beacon 2</u> was chosen to have a superimposed lower frequency of 500 Hz. Therefore, the maximum delay to produce an output from a LM567 with a centre frequency of 500 Hz and a bandwidth of 50 Hz is:

$$\text{Period for 1 cycle} = \frac{1}{500} \text{ seconds}$$

$$\text{Period for 15 cycles} = \frac{15}{500} \text{ seconds} \qquad \ldots\ldots\ldots \quad \text{Eqn B6}$$

$$= 30 \text{ milliseconds}$$

<u>Beacon 3</u> was chosen to have a superimposed lower frequency of 420 Hz. Therefore, the maximum delay to produce an output from a LM567 with a centre frequency of 420 Hz and a bandwidth of 42 Hz is:

$$\text{Period for 1 cycle} = \frac{1}{420} \text{ seconds}$$

$$\text{Period for 15 cycles} = \frac{15}{420} \text{ seconds} \qquad \ldots\ldots\ldots \quad \text{Eqn B7}$$

$$= 35.7 \text{ milliseconds}$$

From the above results, a theoretical angular resolution may be calculated. An average microprocessor interrupt delay was measured to be 40 milliseconds. This is accounted for. For a rotating beacon speed of 51.4 degrees per second (1 revolution per 7 seconds), the angular resolution is:

$$\text{Angular Resolution} = \frac{51.4}{1000}\times(35.7+40) \qquad \ldots\ldots\ldots \text{ Eqn B8}$$
$$\simeq 4^{\circ}$$

B.2 System 2

The following are calculations to determine the angular resolution of system two. The computer crystal frequency is 12 MHz:

$$\begin{aligned}\text{Base Timer Frequency} &= \frac{\text{Crystal Freq}}{\text{Divider Value}}\\ &= 12\times\frac{10^6}{2^{10}} \qquad \ldots\ldots\ldots \text{ Eqn B9}\\ &= 11.71875\ \text{kHz}\end{aligned}$$

The timer resolution is equal to one period of the base timer frequency:

$$\begin{aligned}\text{Timer Resolution} &= 1\ \text{period}\\ T &= \frac{1}{f}\\ &= \frac{1}{11.71875\times10^3} \qquad \ldots\ldots\ldots \text{ Eqn B10}\\ &= 85.3\ \text{microseconds}\end{aligned}$$

The response time of the IS 471F is equal to 800 microseconds. Therefore, the total response time is equal to 885.3 microseconds. The angular resolution is, therefore, as follows:

1 second = 360°

1 microsecond = 0.00036°

Therefore, the resolution in 885.3 microseconds is equal to:

$$\text{Ang. Res.} = \text{Response time} \times \text{Angular Velocity}$$
$$= 885.3 \times 0.00036 \quad \ldots \quad \text{Eqn B11}$$
$$= 0.318^{\circ}$$

B.3 System 3

Calculations to determine the maximum delay between infrared receiver activation and decoded signal output. For an infrared carrier frequency of 350 kHz and implementing LM567 decoders with a 10 percent bandwidth selection, the maximum delay time to produce an output from the decoder is specified as 15 times the number of the input cycles:

$$\text{Period for 1 cycle} = \frac{1}{350\times10^{-3}} \text{ seconds}$$
$$\text{Period for 15 cycles} = \frac{15}{350\times10^{-3}} \text{ seconds} \quad \ldots\ldots \quad \text{Eqn B12}$$
$$= 42.8 \text{ microseconds}$$

Therefore, if the period for capture is 42.8 microseconds and the period for recovery is 42.8 microseconds, then total time to produce one full output cycle will be 87.7 microseconds. The resultant frequency for a period of 87.7 microseconds is:

$$f = \frac{1}{T}$$
$$= \frac{1}{89.7\times10^{-6}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eqn B13}$$
$$= 11669 \text{ kHz}$$

All the beacons centre frequencies are chosen with a 10 percent bandwidth. This selection specified an output response of the LM567 decoders corresponding to an input of 15 cycles.

<u>Beacon 1</u> centre frequency chosen is 11.5 kHz,

$$\therefore \text{Period for 1 cycle} = \frac{1}{11.5\times10^3}$$

$$\text{Period for 15 cycles} = \frac{15}{11.5\times10^3} \quad \ldots\ldots \quad \text{Eqn B14}$$

$$= 1.30 \text{ milliseconds}$$

Beacon 2 centre frequency chosen is 10.5 kHz,

$$\therefore \text{Period for 1 cycle} = \frac{1}{10.5\times10^3}$$

$$\text{Period for 15 cycles} = \frac{15}{10.5\times10^3} \quad \ldots\ldots \quad \text{Eqn B15}$$

$$= 1.43 \text{ milliseconds}$$

Beacon 3 centre frequency chosen is 9 kHz,

$$\therefore \text{Period for 1 cycle} = \frac{1}{9.5\times10^3}$$

$$\text{Period for 15 cycles} = \frac{15}{9.5\times10^3} \quad \ldots\ldots \quad \text{Eqn B16}$$

$$= 1.57 \text{ milliseconds}$$

Assuming a negligible response delay from the timer and a beacon rotation speed of 1 revolution per second, the system angular resolution would be:

$$360^\circ \text{ in 1 second}$$

$$\rightarrow 0.36^\circ \text{ in 1 millisecond}$$

$$\text{System Angular Resolution} = 0.36\times1.57 = 0.56^\circ \quad \ldots\ldots\ldots \quad \text{Eqn B17}$$

B.3 Calculations for resultant system resolution

These tables display the resultant linear variations arising from variations in recorded angular readings. The theoretical angular tolerance that was predicted for system one was 4°. This tolerance value is applied to the resection algorithm to determine the resultant linear variation. The resultant theoretical linear tolerances are discussed in the main text.

Table B-1: Maximum Tolerance Readings for an angular error reading of ± 4°C

	α_1 (°)	β_1 (°)	X_p (mm)	Y_p (mm)	Difference from X_{norm} (mm)	Max X Worst Case (mm)	Difference from Y_{norm} (mm)	Max Y Worst Case (mm)
NORM	120	240	1155	2000	-	79	-	192
CASE1	116	236	1063	2064	92	186	64	256
CASE2	116	244	1242	2178	87	186	178	370
CASE3	124	236	1056	1808	99	193	192	370
CASE4	124	244	1249	1941	94	193	59	237

An angular resolution of 0.5° was applied to the resection algorithm in order to determine an acceptable linear tolerance limit. The variations in linear displacement are presented below. These are discussed in the text.

Table B-2: Maximum Tolerance Readings for an angular error reading of ± 0.5°C

	α_1 (°)	β_1 (°)	X_p (mm)	Y_p (mm)	Difference from X_{norm} (mm)	Max X Worst Case (mm)	Difference from Y_{norm} (mm)	Max Y Worst Case (mm)
NORM	120.0	240.0	1155	2000	-	12	-	23
CASE1	119.5	239.5	1143	2008	12	23	8	16
CASE2	119.5	240.5	1166	2023	11	23	23	46
CASE3	120.5	239.5	1143	1977	12	23	23	31
CASE4	120.5	249.5	1166	1992	11	23	8	16

APPENDIX III

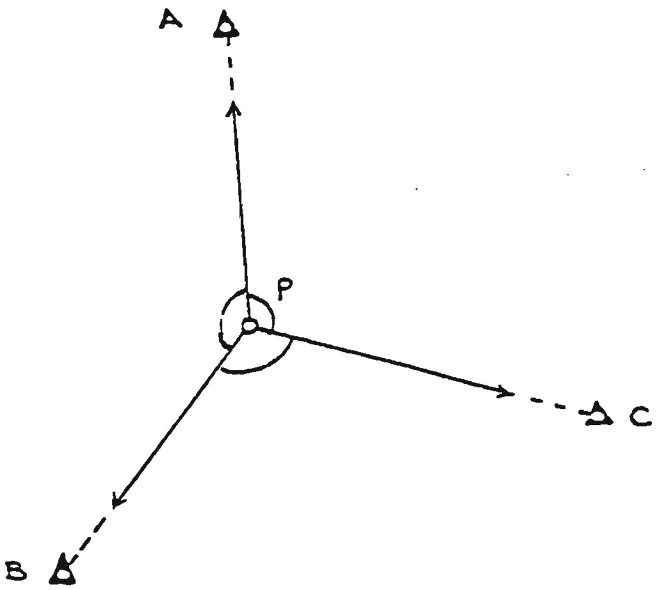
PIN	NAME	PURPOSE
1	Frame Ground	Earth ground for safety
2	Transmitted Data	Data line from DTE to DCE
3	Received Data	Data line from DCE to DTE
4	Request to Send	Asserted by the DTE when it is desired to send information over the communications link. The DCE responds by acquiring control of the link if it does not have it already.
5	Clear to Send	Asserted by the DCE when it has control of the communications link.
6	Data Set Ready	Asserted by the DCE when it is powered on and functioning properly.
7	Signal Ground	Logic ground for the interface
8	Data Carrier Detect	Asserted by the DCE when it is receiving a carrier over the communications link.
9	Reserved	
10	Reserved	
11	Unassigned	
12	Secondary Data Carrier Detect	Same as Data Carrier Detect but for a secondary channel
13	Secondary Clear to Send	Same as Clear to Send but for a secondary channel
14	Secondary Transmitted Data	Same as Transmitted Data but for a secondary channel
15	Transmit Clock	A clock frequency for the transmitter usually used for synchronous communications. This signal is supplied by the DCE to the DTE.
16	Secondary Received Data	Same as Received Data but for a secondary channel
17	Receiver Clock	A clock frequency for the receiver usually used for synchronous communications This signal is supplied to the DCE from the DTE.
18	Unassigned	
19	Secondary Request to Send	Same as Request to Send but for a secondary channel
20	Data Terminal Ready	Asserted by the DTE when it is powered up and functioning properly.
21	Signal Quality Detect	Asserted by the DCE when the communications channel is operating reliably. If negated, the DTE may wish to change the bit rate by changing the level on pin 23, Data Rate Select.
22	Ring Indicator	Asserted by the DCE when something on the communication channel is attempting to contact the DCE
23	Data Rate Select	Used to select the bit rate of the DCE. May be changed in response to a change of pin 21, Signal Quality Detect.
24	External Transmit Clock	A transmitter clock supplied by the DTE to the DCE.
25	Unassigned	

SURVEY CALCULATIONS : THE RESECTION

GIVEN : (i) Co-ordinates of fixed points A,B,C
(ii) Un-oriented observations $\alpha_{PA}, \alpha_{PB}, \alpha_{PC}$

CALCULATE: (i) Correctly oriented directions
(ii) Co-ordinates of P

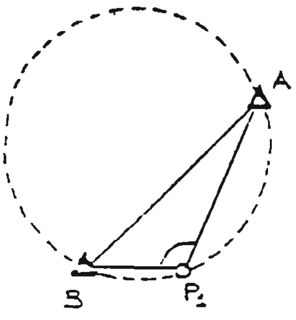
THEORY :

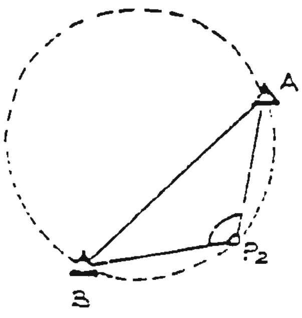


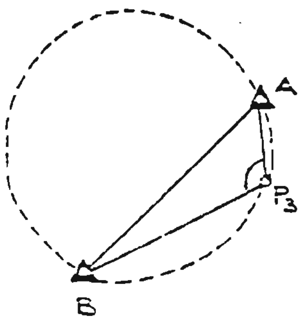
In a resection, observations are taken from the unknown point to fixed points (ie backward observations). These observations are unoriented as no forward observations are made to the unknown point. Even though the observations are un-oriented, the correct angles $A\hat{P}B$, $B\hat{P}C$, and $C\hat{P}A$ can be determined.

Recall: all angles subtended by a chord, in the same segment of a circle, are equal.

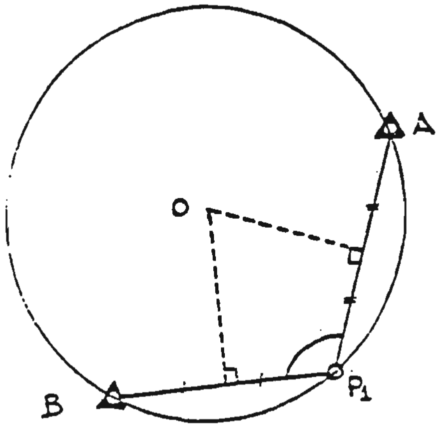
(i) Consider the angle $A\hat{P}B$, and chord AB.







The lines which measure the angle A$\hat{P}$B will intersect at some point P1. If the orientation of rays are changed, the lines will intersect at a new point P2. Repeating this process will give a third intersection point P3. Repeating this process will give a fourth intersection point P4. Points P1, P2, P3.. Pn represent the locus of a point P. This locus is the arc of a circle such that the angle subtended at its circumference by the chord AB is equal to the angle A$\hat{P}$B.



The locus circle can be constructed after the determination of the first point P1 by -

a) joining A-P1 and P1-B

b) constructing the perpendicular bisectors of these chords.

The intersection of the perpendicular bisectors gives the centre of the circle (O).
The unknown point P lies somewhere along the circumference of the locus circle passing through A and B.

(ii) Consider the angle A$\hat{P}$C and chord AC.
Point P lies somewhere along the circumference of the locus circle passing through A and C.

(iii) Consider the angle B$\hat{P}$C and chord BC.
Point P lies somewhere along the circumference of the locus circle passing through B and C.
Point P is the common intersection of the 3 locus circles.
This gives a unique determination of the position of P.