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DIGITAL GUIDANCE OF AN UNMANNED BATTERY ELECTRIC VEHICLE

by

JOHN STANLEY DAVENPORT

A Thesis Submitted for the
DEGREE OF DOCTOR OF PHILOSOPHY
to
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FORWARD

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SUMMARY

Automation in industry provides both cost and management benefits. Within the materials handling field, these benefits are provided by automated guided vehicle systems. Currently available systems suffer from the problems of path and vehicle dependence, i.e. the need for a guide wire and the customised nature of the automatic equipment which is only suitable for the vehicles with which it is supplied. Future systems will need to be more complex whilst maintaining the ability to suit the smaller, simpler systems. More interfacing with other automatic manufacturing and warehouse equipment will be needed and the vehicles themselves will need more intelligence.

A free-ranging, autonomous, intelligent, automatic vehicle would overcome the present limitations and simultaneously meet the expected future requirements. This Thesis describes a research programme which is adequate to develop such a vehicle. This includes the design of a materials handling system which can operate equally well with both simpler wire guided vehicles and the more complex free-ranging vehicles. The design is based on the concept of delegated intelligence where the vehicle sub-systems are all controlled by microprocessors. The major advantage of automated guided vehicle systems is the flexibility they give to the materials handling operation and this is a direct function of the intelligence of the system. The provision of intelligence in the vehicle sub-systems has a major impact on the flexibility of the complete system.

An automatic vehicle has various sub-systems of which the most immediate is steering. The vehicle steering system is designed in a modular manner. A mathematical model of the steering system has been developed and validated, and the building of the steering system on the basis of this model means that future system development will be for the sensors only and will be rapid. The control of the steering function by a microprocessor gives the system great flexibility, particularly with the use of software controlled manoeuvres.

Key Words: Automated Guided Vehicle System
Control Theory
Vehicle Kinematics

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PREFACE

The work described in this report was carried out under the Total Technology (TT) Section of the Interdisciplinary Higher Degrees (IHD) Scheme at the University of Aston in Birmingham. The IHD Scheme was set up with the purpose of establishing and encouraging links between the University and industry. Under the Scheme, problems presented by a commercial organisation are studied by students registered at the University. This enables research to be carried out in conjunction with the University which has direct applications for current, practical problems in commercial organisations. The TT Section of the Scheme focuses particularly on technological problems.

There are many advantages to this Scheme. Firstly, the University forges closer links with industry. At a time when our Universities are under attack from many quarters, this can only help to strengthen the position of the University within the National Community. Furthermore, the feedback gained from this contact will enable the University to relate its courses and curricula more closely to the needs of industry in this country. Secondly, industry gets a closer look at the University. The better industry understands the educational procedure within our Universities, the better it will understand the graduate who emerges from them. Then it will be able to use those graduates to greater effect and replace the competitive edge that so much of British industry seems to have lost. Finally, the student sees both aspects of research - the academic and the commercial. In this way he learns to understand the huge gulf between the basic knowledge, and the realisation of that knowledge in a practical process or product. This enables him to be much more adept at turning concepts into saleable hardware (and with the increasing use of digital techniques in industry one ought there to include saleable software!).

Thus the IHD Scheme serves the University, industry and the student. It is an excellent way of providing the crosstalk so badly needed between industry and academia and I personally am very pleased and grateful to have been involved in it.

J DAVENPORT

DECLARATION

The work described in this Thesis, which was performed in collaboration, is described as such and none of the work has been submitted in support of a Degree or other award at this or any other Institution.

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CHAPTER 1

THE SPONSORING ORGANISATION

INTRODUCTION - THE BIRTH OF THE PROJECT

1.1 OBJECTIVES

It is the aim of this introduction to give the conceptual background to the project. This will be done by looking first at the sponsoring organisation and then at a statement of the project. The sponsoring organisation will be examined in terms of its history and development and its present position as defined by its products and the markets in which it operates. The statement of the project will outline the research programme of which this project is a part and then focus upon those aspects which relate directly to this project. In this manner, a framework will be established within which the project development can be viewed and understood.

1.2 THE SPONSORING ORGANISATION

The sponsoring organisation is Cableform Limited which is a wholly owned subsidiary of the public quoted company Comtech Limited. The Chairman of Cableform Limited is Mr P Moody and there are eight other directors. Their responsibilities include the management of an American subsidiary, owned by Cableform Limited, set up in 1974 to exploit the large potential market in North America. The work described in this report was carried out in the research department of the company.

1.3 CABLEFORM'S HISTORY AND DEVELOPMENT

Cableform Limited started trading as a small private company in Stockport, Cheshire in 1948. In the early days, the company specialised in the manufacture of wiring harnesses on a sub-contract basis and supplied them to the manufacturers of aircraft, textile machinery and road laying plant. This involvement in electric machinery led naturally to the development of direct current contactors which in turn directed the company's attention to control systems. It was at this point, in the late fifties, that the company's association with battery electric vehicles became significant. In the early sixties, it was recognised that serious penetration of these markets would require a thyristor controller to be added to the product range. Following a period of development, the forerunner of the present Pulsomatic system was introduced in 1970. The Pulsomatic system, now in its second generation, has been improved and broadened to the point where it now fits many battery electric vehicles directly and can, with a little customising, be fitted to any battery electric vehicle. This independence of the controller from the vehicle is the hallmark of Cableform's products and it is central to their operating philosophy.

From the control of the traction of a battery electric vehicle, attention turned to the control of all vehicle functions including traction, steering, load handling and transport. In view of the fundamental nature of some of the problems involved in the development of these control systems, the research department was set up in 1979 to investigate the development of systems necessary to control an unmanned battery electric vehicle. Furthermore, following the design philosophy at Cableform, these controllers were to be independent of the vehicles to which they will be fitted. At the present time (November 1982) a development plan has been established and the development of the first project in that plan is well established.

1.4 CABLEFORM'S PRESENT POSITION

The present position of the company can be described in terms of its products and its market position.

1.4.1 Product Range

Cableform's systems and components range includes electronic speed controllers, direct current (d.c.) contactors, battery connectors, hydraulic pump controllers, d.c./d.c. converters, battery discharge indicators and all the associated components necessary to connect and control the motor and the battery. The motor controllers can accommodate shunt or series wound motors of any d.c. voltage. The system is designed on a modular basis, and it is this modular design which gives the system its great flexibility. The controllers are built from three fundamental units, each of which is selected from a basic range. The three units are: a speed control unit, a motor control unit, and a power control unit. Each unit is a fully specified device and can connect with any of the other units throughout the entire system range. Figure 1.1 shows the three units and the various interconnections between the units, the motor, and the battery. The modular design also ensures that the

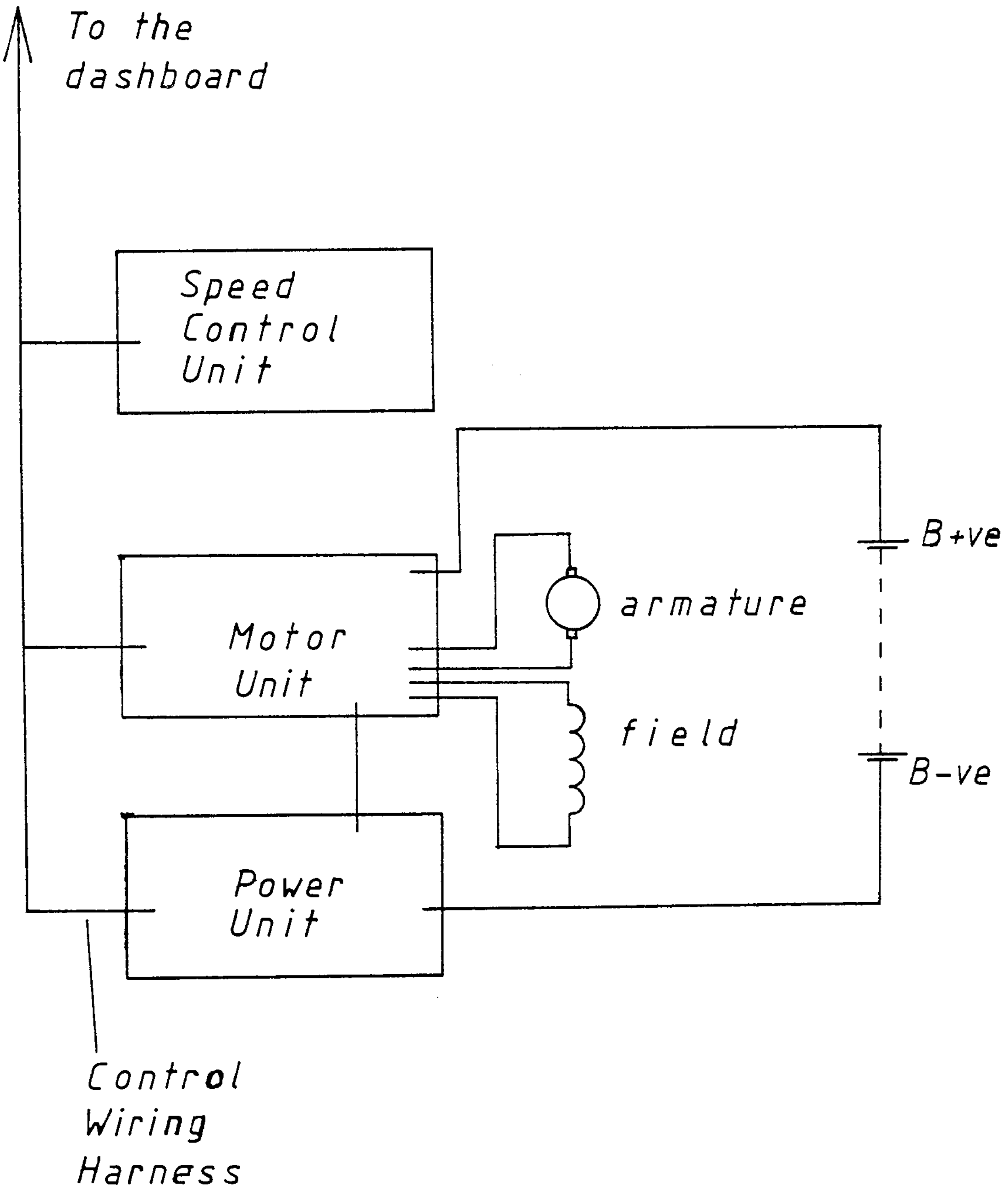


Figure 1.1 - Cableform's Modular Motor Controller

interconnection harness remains the same whatever particular units are being used on a given controller.

In addition to the basic control system, various special control features may be added, such as field weakening, regenerative braking, speed limitation, etc. Over the years, this system has shown itself to be a highly reliable, technically advanced and flexible controller, and has gained from its reputation a growing share of the international market.

1.4.2 Market Position

Originally the prime targets for sales were the industrial truck and road vehicle manufacturers in the UK. Figure 1.2 gives the UK sales of industrial trucks from HMSO Business Monitors in recent years and as can be seen the UK market shows no real signs of expansion. In the late sixties, however, attention was directed overseas. Today Cableform exports about 50 per cent of its production and regular sales are made in the following countries:

Italy
Switzerland
Bulgaria
Finland
South Africa
Zambia
Canada
Spain
Malaysia
Germany
Belgium
France
South America
Norway
Israel
Sweden
Australia
USA
New Zealand
Holland
Denmark
Eire

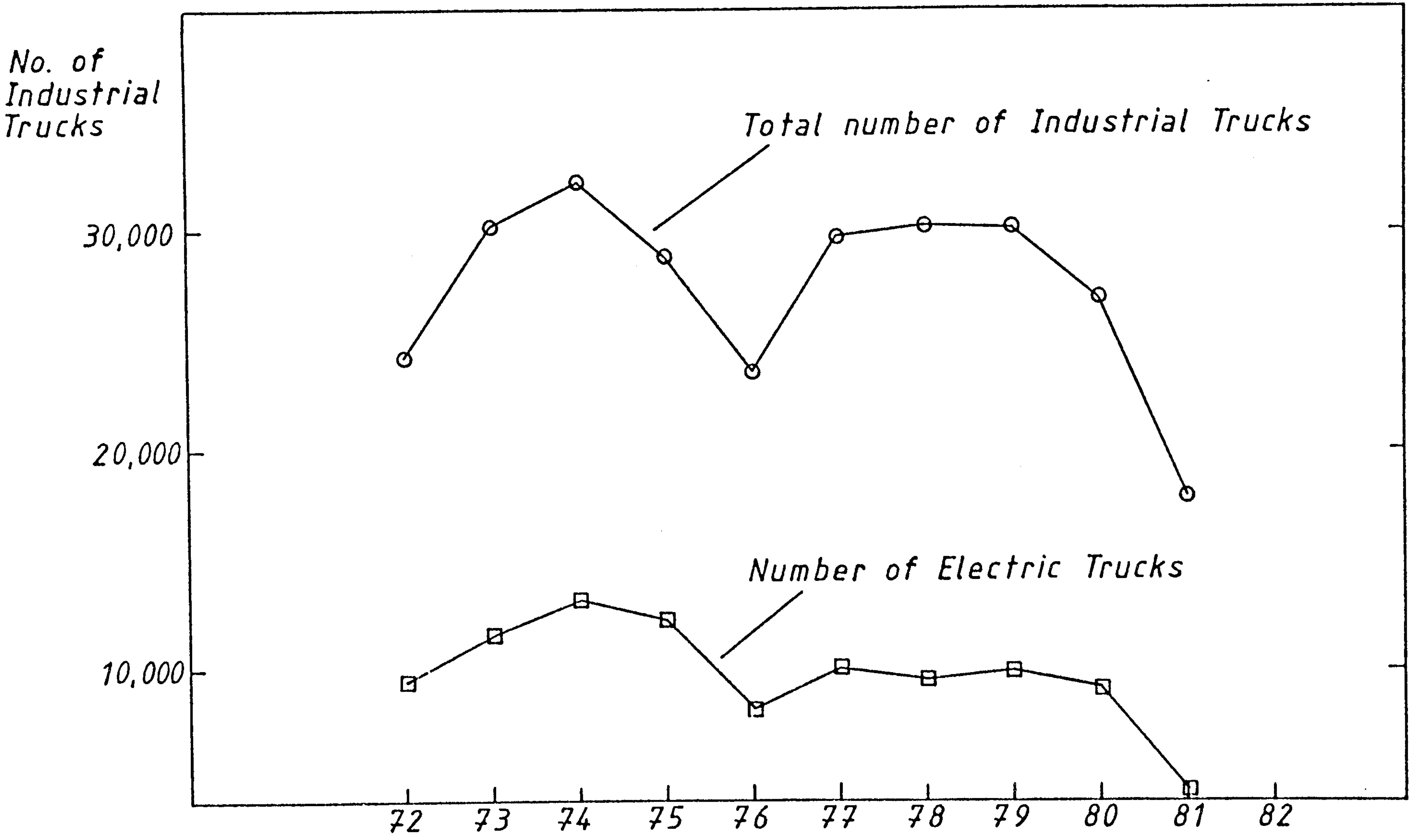


Figure 1.2 - Industrial Truck Sales in the U.K.

The world market for electric vehicles can conveniently be divided into five groups, and Table 1.1 is a breakdown of the market showing Cableform's present (1981) position with regard to controllers.

Region	Number of E.V. Units / Annum	Number of Cableform Units/Annum	Cableform's Market Share
Western Europe	33,000	5,250	16%
Eastern Europe	60,000	1,000	2%
North America	27,000	5,000	19%
Japan	16,000	250	2%
Rest of world	5,000	500	10%
Total	141,000	12,000	8.5%

Table 1.1 - The World Electric Vehicle (E.V.) Market

With two exceptions, accounts are serviced from the UK. In the case of North America, a subsidiary company was incorporated in Virginia, whilst in Germany a sales office was set up, supervised by a German national employed directly by Cableform.

Thus the concept of a highly flexible, vehicle independent controller has enabled Cableform to gain a competitive market position. It was with the aim of securing and increasing this position that the present research programme was initiated.

1.5 CABLEFORM'S RESEARCH PROGRAMME

In the last twenty years the mechanical handling and storage field has seen a number of improvements in the provision of mechanical aids, but little, until recently, in the form of automation. However, with the advent of the microprocessor, large scale changes in production and materials handling methods are becoming possible. In particular, the possibility of installing a considerable amount of intelligence on a battery electric vehicle shows much promise of developing a highly versatile robot vehicle which will be able to interface automatically with both existing materials handling equipment and the many computer controlled devices now appearing on the industrial scene, such as automatic storage and retrieval systems, computer numeric controlled machines, flexible manufacturing systems etc. Already several companies are offering automated guided vehicle systems of which perhaps the most famous is the Fiat Mirafiori factory in Turin. These systems provide driverless vehicles, which are usually inductive wire or white line following, and some measure of central control. Communication between the central control and the vehicles gives a large degree of flexibility in the materials handling function. However, the vehicles are constrained to follow pre-determined routes and so the systems can be seen as fixed path systems no different in concept from a conveyor, merely possessing more flexibility. The logical development to these systems is a free-ranging vehicle which can generate its own path from environmental information. This then would be a variable path system and the vehicle could not truly be described as 'driverless' since the guidance function would perform all the tasks presently performed by a human driver.

The aim of the research programme at Cableform is to develop control systems for the automatic and remote control of electric vehicles. In order to maintain the independence of the controller from the vehicle, the control systems will be based on digital techniques such that the parameter variation represented by different vehicles can be met by software changes, thus avoiding expensive hardware alterations. The product will consist of a central control unit to co-ordinate the activities of a number of vehicles in response to user requests, and controllers suitable for the automatic control of an electric vehicle and its load handling equipment. While it is appreciated that the initial developments will be path-defined systems, the final vehicle will be free-ranging. A functional description of such a vehicle is given in Figure 1.3 in which the main vehicle functions are seen to be guidance, communications and load handling. Guidance comprises the navigation and control of the vehicle. Communications forms a link between the individual vehicle and the overall system control or Central Control. It provides Central Control with status information on each particular vehicle, and provides each vehicle with information about the other vehicles and changing aspects of the environment. Load handling includes all the vehicle functions involved in materials handling in industrial situations.

This report describes the establishment and initial development of this research programme. Four major areas of work are involved. Firstly, the programme was drafted in a form which was both technically feasible and commercially acceptable. Secondly, an investigation into wire guidance sensors was carried out. This

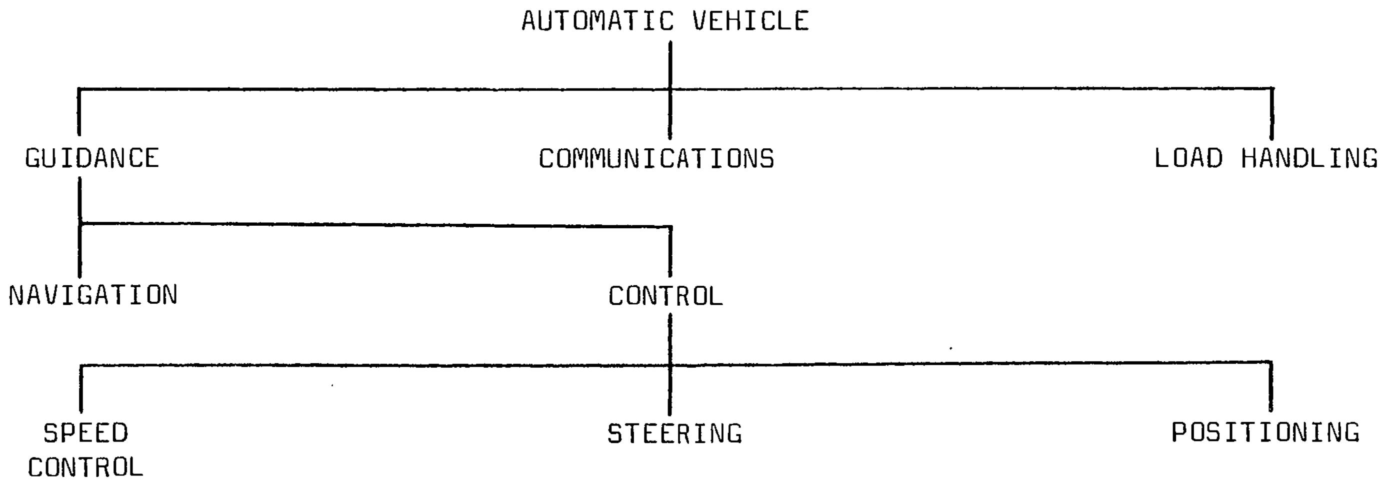


FIGURE 1.3 – FUNCTIONAL DESCRIPTION OF AN AUTOMATIC VEHICLE

involved the development and validation of a mathematical model of the sensor.

Thirdly, an investigation into the steering system was carried out. This involved the development and validation of mathematical models for both the steering motor in its control loop and the vehicle lateral response. Finally, hardware systems were designed and commissioned to operate on a test vehicle at the sponsoring organisation. Thus the work established the theoretical background for the steering system upon which all future controllers will be based, and successfully developed the first generation steering system controller.

1.6 JUSTIFICATION OF THE RESEARCH PROGRAMME

It is appropriate at this point to look at the justification of the whole programme of research from the point of view of the sponsoring organisation. The research will bring major benefits to the company, including:

(a) Increased sales - The extension of the product range into the automatic control of battery electric vehicles will enable Cableform to establish their presence in a market which is expanding.

(b) Product Diversification - The extension of the product range will provide the company with some immunity from the continuing effects of economic depression upon the electric vehicle market.

(c) Improvement of Existing Products - The technology used and the techniques developed will enable improvements to be made to existing products which will allow Cableform to sell at more competitive prices, thus increasing their market penetration and their profits.

(d) Greater Understanding of Vehicles - A natural consequence of the research will be a greater understanding of vehicles and how to control them. This will enable Cableform to make more reliable and more easily maintained products.

1.7 SUMMARY

Cableform Limited market controllers for the traction of battery electric vehicles. A natural extension of their product range would be to include the control of other vehicle functions such as guidance. Following Cableform's design philosophy the controllers must be independent of the vehicles to which they will be fitted. In view of the fundamental nature of some of the problems involved in the development of these control systems, a programme of research was set up. A part of this research programme is the development of a lateral position control system.

CHAPTER 2

AUTOMATED MATERIALS HANDLING SYSTEMS

2.1 OBJECTIVES

This Chapter looks at the state and the art of automation in industrial materials load handling. Following a short historical background, a justification of the use of automation in industry, both in technical and commercial terms, is given. The techniques, vehicles and methods used in both load transport and load handling are described. To give an idea of the many possible uses of automated guided vehicle systems in industrial load handling, three examples are given showing such systems interfacing with manned operations, interfacing with automatic operations and providing a complete fully automatic operation. Finally, future system possibilities based on the light of current research are reviewed.

2.2 INTRODUCTION

The concept of automatic control is nothing new. The first application of feedback control was in the development of float regulator mechanisms in Greece in the period 300 to 1 B.C.[1,2]. The first automatic system to be invented in modern Europe was the temperature regulator of Cornelis Drebbel (1572 - 1633) of Holland[1,2]. The first automatic feedback controller used in an industrial process is generally agreed to be James Watt's flyball governor developed in 1788 for controlling the speed of a steam engine[1,2].

In the materials handling field, although devices have been developed to amplify man's capabilities, little was available in the way of automation until recently. With the exception of conveyors, which can only be cost justified on high density routes, it still needed a man to move with the materials. With the advent of the EMI Robotug in the early 1960's[3], however, it was no longer necessary to have a man travel with the load, and the automation of individual vehicles for use in materials handling had started.

In control terms the EMI Robotug was a very simple machine, needing to be manually dispatched and received. In effect it simply replaced a conveyor. The problem, in common with all early systems, was that it did not have the large scale data analysis and processing capability necessary for a centrally controlled automatic materials handling system. With the increasing use of computers in industrial environments, more sophisticated systems became possible. One of the earliest computer controlled systems was installed in 1965 in an aircraft engine overhaul and repair centre in the USA[4]. These systems allowed the remote dispatching and receiving of vehicles, thus introducing the need for a transmission link to allow for data transfer to and from the vehicles. At first radio was used as the transmission link, but later the wire guidance system was adopted to allow for data transmission at selected 'communication sites'.

The speed and flexibility of these systems was limited due to the fact that all the intelligence was in the central computer and so all the system decisions had to be made there. However, in the early 1970's, the advent of the microprocessor meant that the vehicles could be given much more intelligence and so the central computer was freed of the need to make low-level functional decisions and could concentrate more directly on the control of materials movement, vehicle availability and other such higher-level considerations. The central computer now only had to send a high-level command to a vehicle such as 'take the load from position m and place it in stock location n', and the on-board vehicle intelligence would take care of all the low-level functional commands needed to physically make the vehicle move the load from position m to stock location n. Since the mid 1970's then, the growth in the use of automated guided vehicles (AGV) and automated guided vehicle systems (AGVS) as an integral part of a complete automatic materials handling function has greatly increased.

The use of an AGVS in a commercial operation, however, is not merely a matter of technical suitability. The system must be cost justified too, and wire guided systems do not come cheap. Automated trucks cost about £15,000 each[22,32], the central controller costs in the region of £3,000[22,32] and with the wire (including installation) costing anything up to £50 a metre, even a simple four truck installation with about 6,000 metres of track can cost £350,000[42]. For commercial organisations to pay these figures for a handling system there must be some cogent benefits indeed. High though these costs may appear, they must not be viewed in isolation.

A normal fork lift truck costs £10,000 and the cost of a driver for one shift over the year is around £10,000[43]. A comparison of operating costs between different transport systems by Thomas Mueller of the Technische Universitaet, West Berlin[8], shows that AGVS are cheaper than other individual vehicle systems over all except the shortest distance routes. His curves for conveyors and mono-rail systems do not include installations costs which are significant for low capacity or long distance routes. Thus, except for high capacity short distance routes where conveyors are cheaper, AGVS can be justified on a cost basis alone. Following Quinlan, three major reasons can be identified behind the increasing attractiveness of AGVS as a transport method[4].

(a) Better Guided Vehicles. Initially the vehicles had no on-board intelligence and merely ran to the programmed stop after being manually dispatched. However, with the increasing complexity and decreasing cost of electronics in the past two decades, much of the system intelligence can now be put on the vehicle. The vehicle can be remotely instructed, reprogrammed and dispatched. It can check its own battery condition and go to automatically recharge itself. Thus, the vehicle is easy to use and hence more attractive to the end user.

(b) Greater Industrial Automation. The increase in the use of automation in industry generally has made the use of AGVS more acceptable and the interfacing of the AGVS with other automatic systems was a natural extension of the concept of automatic control. Thus, the use of an AGVS with, say robot welders[5] or an automatic storage and retrieval system[6], is gaining widespread attention in industry, and the proliferation of Computer Numerically Controlled (CNC) machine tools will further increase the demand for AGVS.

(c) Demand for Productivity. AGVS provide management with an efficient information system as well as a flexible production tool and this means cost savings and greater productivity. The

National Materials Handling Centre at Cranfield estimates that 39% of this country's Gross Domestic Product (£50,000 million in 1979) is absorbed by materials handling in its widest sense[7]. The use of AGVS to streamline and rationalise materials handling can cut costs in terms of fewer people needed and extended machine life due to optimal use, and can increase productivity because the communications ability means that double runs can be operated and the optimal automatic operation of the vehicle (i.e. no sudden starts, stops or changes in direction which lead to fatigue) increases machine life time and cuts down time for maintenance and repair.

Thus, the basic concept behind the use of AGVS is to provide a cheaper and more efficient materials handling system. The ability of AGVS to do this, and in fact the use of automation in industry generally, has been greatly aided by the following factors:

<u>Growth of product lines.</u> With the continued development of the consumer society, product variety has increased in all market sectors. Furthermore, the trend towards larger warehouses and distribution centres to provide for economies of scale in storage means that the number of product lines stored increases still further.

<u>Growth in information flow.</u> With the increased number of product lines stored, the flow of regulatory information increases. Also the larger depots require more formalised accounting techniques which also tend to increase the amount of recorded information. The only way to control this large amount of information quickly, accurately

and economically is by computers, and the use of computers imposes a formalised information flow scheme which is ideally suited to the automatic operation of the system components.

Increased labour costs. With the ever increasing cost of labour any way of reducing labour costs is well worth investment. The use of AGVS not only cuts direct labour costs by reducing the number of operatives necessary, but with the rationalisation of the materials handling system that the use of an AGVS provides, indirect labour costs in terms of support personnel, clerks, etc. are also reduced. Staff reductions of 29% have been recorded[7]. It is interesting to note that AGVS is more developed in countries such as Sweden, the USA, and West Germany where labour costs are higher than in the UK and where the cost benefits are correspondingly greater. A natural corollary of this is that with the ever increasing cost of labour in the UK and the continuing fall in the cost of electronics, AGVS will become more and more competitive in the years ahead and a much greater proliferation of AGVS in the materials handling market can be expected.

Improving safety. Automation of any industrial activity enables the designer to incorporate fail safe mechanisms for the protection of employees. AGVS provide safety features such as speed regulation, automatic slowing down for corners and constant obstacle detection warning systems; at a time when many companies find it cheaper to pay the fines after accidents rather than train their truck operators[24], such features can only increase the standards of safety. Of course in a completely automated operation the safety level reaches 100% since there are no human operatives to be endangered.

Increasing productivity. Human operatives generally execute tasks in a sequential manner. However, with the use of automation, simulataneous operation of multiple tasks is possible. This speeds up the truck operating cycle. Furthermore, the instant communications and remote reprogramming ability of an automatic system can increase productivity[52] by reducing the number of single run operations of each truck, and route optimisation programmes further reduce cycle times.

Reduced capital costs. Shorter operating cycles mean that fewer trucks can perform the same operation, thus, reducing fixed capital costs.

Reduced running costs. Automated operation of the trucks increases the operational life of the truck and reduces maintenance bills. Automatic operation means that there are no sudden starts, stops or changes in direction and reductions of 30% in maintenance bills have been recorded[22,23].

Reduced storage costs. By reducing lead time from storage, savings can be realised by the consequent reduction in stock holding. Ilford at Basildon expect to save in excess of £0.5 million over a five year period due to reductions in the manning levels, the number of trucks required and an £275,000 reduction in stock holding following the introduction of a computer controlled pallet handling system[24].

Thus the use of automation in general and AGVS in particular provide the following advantages:

(a) Reduced labour, maintenance and capital costs.

(b) Real time production and inventory control.

(c) Increased productivity and flexibility.

(d) Reduced parts handling.

(e) Safe and consistent handling of loads

to which can be added the energy savings given by AGVS. The automatic operation of the vehicle uses up to 30% less energy than a human operator[42] and if there are no human operatives present in the facility then savings on heating and lighting can be up to three times the savings in direct labour costs[42,44]. The investment payback period on AGVS is reported around 18 to 24 months[22,23]. Even on a three year lifetime, and AGVS have been operating continuously for 18 years now[45], the investment capital can be adequately realised.

Quinlan[4] sees the following expected features on future systems:

(a) Larger, more complex AGVS.

(b) A continued need for the smaller, simpler system.

(c) More interfacing with other automatic manufacturing and warehousing functions.

(d) More intelligent AGV's.

The provision of an intelligent AGV would meet all of the above features. On its own, an intelligent AGV would provide the needs of the smaller, simpler systems with a vehicle mounted keypad to allow for instructing the vehicle. The replacement of the keypad with a communications link would allow the AGV to interface with other automatic functions, and such an intelligent, remotely addressable

AGV would fit easily into a larger system wherein the main computer need concern itself only with the high-level materials handling functions and not with the lower-level machine actions.

In this manner, the intelligent AGV is central to the continued development of more effective and flexible materials handling. In any materials handling operation, two distinct operations can clearly be identified:

(a) Load transport.
(b) Load handling.

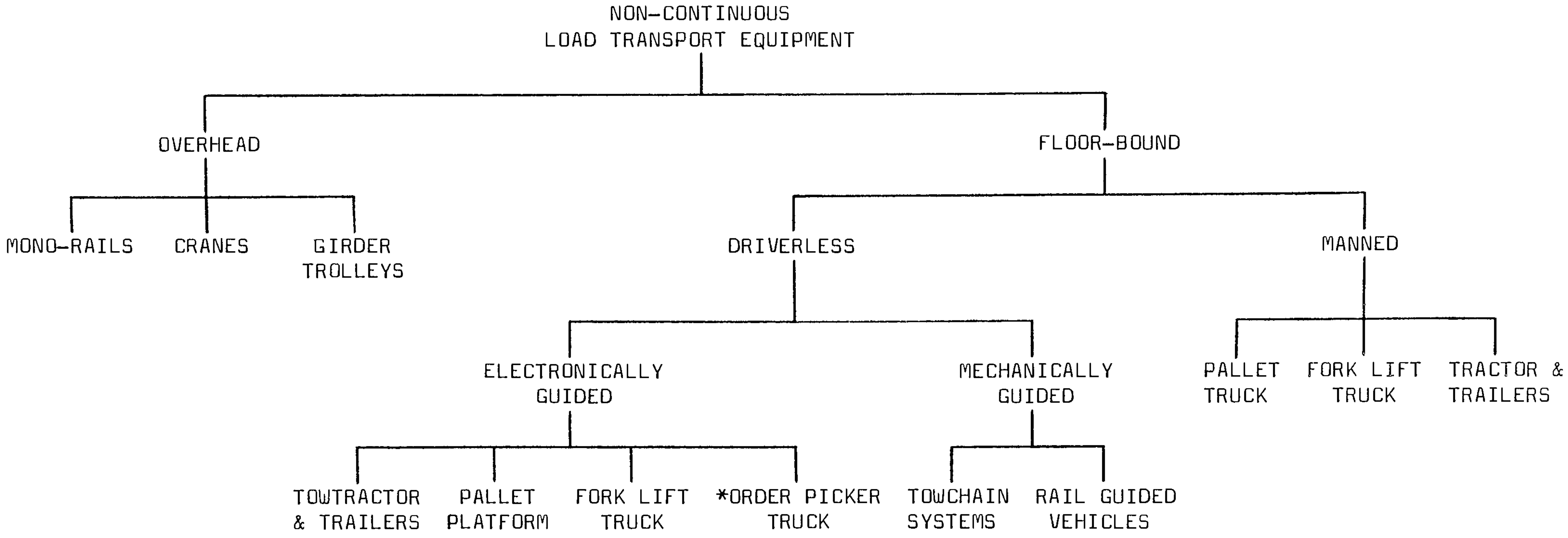
In order to investigate the requirements of an AGV which is to perform these operations in a modern industrial environment, these two categories will now be examined more closely.

2.3 LOAD TRANSPORT TECHNIQUES

2.3.1 Classification Categories

To distinguish between the movement of goods from one location to another by a single transport mechanism, and the transfer of goods from one mechanism to another, the former is termed load transport and the latter load handling. Load transport is concerned with the task of moving materials from one location within the plant to another location also within the plant. The choice of load transport mechanism will depend on such factors as the size, shape and weight of the load, the terrain to be covered, the required speed of conveyance, the distance to be travelled, the density of material movement and the flexibility required of the transport system. There are various classifications of load transport mechanisms that can be made, but following Mueller[8] a basic distinction can be made between continuous and non-continuous mechanisms. Continuous mechanisms are conveyors and can only be cost justified on high density, short to medium distance, low flexibility routes, although more modern conveyor systems do allow for some flexibility. On such high density routes their cost benefits are clear and they are to be preferred. Where quantities are small, production flexible, products varied, and the area to be covered considerable, discontinuous handling by industrial trucks will be more economical (except where unit loads of abnormal size or weight compel the use of heavy-duty conveyors or cranes)[18]. The individual vehicles used may be manually operated or automatic. In the latter case, distinction must be made between floor-bound and overhead systems. Of the driverless systems, the inductive loop or wire guided technique is by far the most wide-spread, with other electronic systems and mechanical systems having little importance. A classification for non-continuous transport systems, based on Mueller's, is shown in Figure 2.1.

Since the introduction of the first driverless trucks in the early 1960's much has been done to improve the control of the vehicles in terms of their performance within the total materials handling system. However, despite these advances, little has been done to improve the wire-guided vehicle itself and the method of guidance has remained exactly the same. Although the method works, its operation has never been properly investigated and as Larcombe[9] notes: "Extension of the capabilities of automatic guided vehicles requires an understanding of the guidance mechanism. There are



* Wire Guided in the aisle only.

FIGURE 2.1 - NON-CONTINUOUS LOAD TRANSPORT EQUIPMENT

clearly opportunities to render existing systems more reliable and more flexible by combining such understanding with existing sensor systems and electronic switching systems".

2.3.2 Guidance Methods

Of the many possible guidance methods (tow chain, rails, UV stripe, fluorescent stripe, etc.) wire or inductive guidance is by far the most widespread. The inductive guidance method consists of two coils mounted on the vehicle and a guide wire which in most applications is buried to a depth of a few centimetres in the ground. An alternating current signal is sent down the guide wire and this produces a magentic field around the wire. The time varying flux of this field induces voltages in the two coils, according to Neumann's law, and these voltages when amplified are used to provide the error voltage which controls the steering of the vehicle and constrains it to follow the wire. The simplest way to do this, and the manner that is universally described in the literature[10-14] is to arrange the two coils to be symmetrical about the wire when the vehicle is in the desired lateral position. Then the difference in the two coil voltages is used as an error signal. If the vehicle is in the desired position, the voltages induced in the two coils will, by symmetry, be equal and the error voltage, their difference, will be zero. Thus, no steering correction will be applied. If, however, the vehicle should wander off course and thus bring one coil closer to the wire than the other, then the voltage in the coil nearer to the wire will be greater, and the voltage in the coil further from the wire will be correspondingly less. The difference will now no longer be zero and depending on the sense of the error voltage, a steering correction will be applied. This will be in such a direction as to bring the vehicle back towards the wire and so equalise the voltages in the two coils.

The most usual manner of producing the error signal[10-14] is to obtain a sum and difference signal. In producing the difference signal it is usual to wind one coil in opposition to the other such that their voltages are 180 degrees out of phase, and algebraically sum the voltages. Thus, if the two coils had equal voltages induced in them, their algebraic sum would be zero. The sum signal, which is often produced by separate extra coils, is then used as a reference against which to compare the difference signal. If the two signals are in phase, this indicates a turn in one direction, and if they are in phase opposition, then this indicates a turn in the opposite direction. Thus, the magnitude of the difference signal gives the rate of turn applied to the steering gear, and the phase of the difference signal with respect to the sum signal gives the direction in which to turn.

With suitable circuitry it is possible to produce both the sum and difference signals from just two coils. However, almost universally four coils are used; two to produce the difference signal, and two to produce the sum signal. The sum signal is often also used as a status indicator. If the signal is above a certain threshold value, then this indicates that the guide wire is energised and the system is functioning properly. In the absence of this signal, suitable circuitry would stop the vehicle and set an alarm indicator. The theoretical sum and difference signals are shown in Figure 2.2.

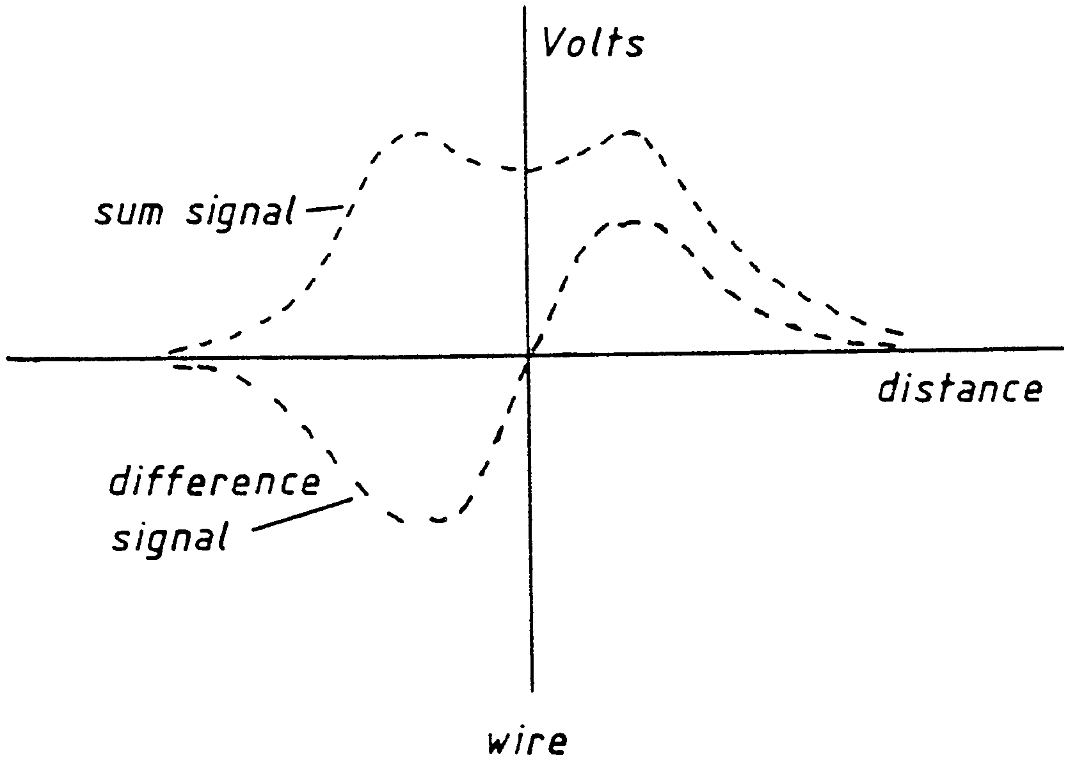


Figure 2.2: Theoretical Sum and Difference Signals

Another method of guidance used by Digitron and Eaton-Kenway provides both traction and steering. The trucks they use are pallet trucks, which are equipped with two wheels driven by separate motors near the centre of the vehicle and four castors, one at each corner, for stability (see Figure 4.3). The two coil voltages are now applied, after amplification, to the two drive motors. Thus, equal coil voltages would drive the motors at equal speeds and so the vehicle will travel in a straight line. However, different coil voltages will mean that the motors are driven at different speeds and so the vehicle will turn in such a manner as to reduce the voltage difference. Due to the basic symmetry of the vehicle, provision of two sets of coils, one at either end, and suitable switching circuitry means that the vehicle can move with equal ease in either direction.

These guidance methods are used almost universally in the field of driverless industrial vehicles. They work well, though not optimally and better performance could be realised if they were better understood. Indeed the fact that the first system works at all is due to serendipity[9]. Thus, an investigation into the guidance method would enable present systems to be better used, and future systems to be better designed to provide swifter and safer automatic guidance.

2.3.3 Transport Methods

Within the field of driverless trucks, four categories stand out as the basic forms of load transportation.

(a) Towtractor with trailers. (See plate 2) The tractor is inductively constrained to follow the guidewire and the load is put into the trailers. These trailers may be of the bin type to accept order picking loads or of a platform type to accept large or palletised loads. The platform type of trailer may be a simple platform or may have a conveyor construction to interface with chain or roller conveyor systems and thus allow automatic load transfer. This type of system was among the earliest AGVS.

(b) Pallet platform. (See plates 4 and 5) Essentially a smaller version of the above, this consists of a single inductively guided vehicle which is a platform onto which the load is deposited. It may be just a flat surface, in which case it must be loaded manually, or it might have a conveyor structure to enable it to interface with conventional chain or roller conveyor systems. Another possibility is a lift table which can load and unload at pedastal type pick-up points. Some loads, such as hospital bins, have stilts themselves and so a simple lift table is all that is required. Some manufacturers (e.g. BT Rolatruc, Digitron) will undertake to fit customised load fixtures.

Another version of the platform truck is the unit load transporter where the truck is designed to carry the basic unit of a production line. The production line now no longer need be of the classic linear design, but can be of any form, as the vehicle is now programmed to take the load to the next operational stop, wherever that might be[15,16]. Thus, the available floor space can be better used and the psychological stress of production line working can be reduced. This situation lends itself perfectly to automation of production operations and perhaps the best known example of this is the Fiat Mirafiori factory in Turin[15].

A development of this which has been used by Volvo at Kalmar[27] is to have the car shell on a unit load transporter. This is then operated on by a group of workers who between them have all the skills necessary to build up a complete car. The tools and materials needed to build up the car are brought to the group on automatic transport and the group then build up the car. This system has been proposed as a way to provide better working environments. Traditionally, each worker had a single job to do on each unit which passed through the factory and his pride in his work and job satisfaction were low due to the fact that he had no identification with the final product. Using the new system, however, a group of workers make a complete unit out of the component parts. The resulting identification with the finished article not only increases the workers' job satisfaction but due to the new pride the workers have in their work, the quality of the product increases too. Thus, the use of AGVS with advanced manufacturing ideas can produce social as well as commercial benefits.

(c) Fork lift trucks. (See plate 3) The trucks follow the route defined by the guidewire, and there are various loading and unloading points en route. Some trucks must be loaded and unloaded manually while others may load and unload automatically. One method of automatic load transfer is to have the load positioned accurately on the guide wire (e.g. Jungheinrich, Babcock). Another method is to provide the vehicle with some sort of sensing to determine its position relative to the pallet (e.g. Carrago-infrared; BT Rolatruc-radar). A variation of the first method is provided by Wagner who can deposit loads on either side of the track from a minimum height of 400 millimetres to a maximum height of 2600 millimetres. This obviates the need for reversing along the branch lines to the load which is a slow, time consuming operation.

(d) Order picker trucks. Although these trucks will carry a human operator who controls the vehicle around the warehouse, an increasing number of suppliers provide wire guidance of the vehicle upon entry to the narrow aisles. The driver then need only concern himself with the positioning of the picking mechanism. With the increasing diversity of product lines, particularly within the consumer market, this type of vehicle will become more and more important in the 1980's.

These then are the four major load transport techniques for use with inductively guided vehicles. They operate under automatic control at speeds between 0.5 ms^{-1} and 1.0 ms^{-1}. Most of them automatically slow down when approaching corners, except for the slowest which are already going slowly enough. They can carry loads from 200 kilograms up to around 2,000 kilograms for a single vehicle. Units with trailers can carry up to around 5,000 kilograms with the notable exception of the Malthouse Hunter equipment which can carry loads up to a staggering 23,000 kilograms[28].

Table 2.1 shows the major manufacturers of automated guided vehicles together with the types of vehicles which they supply.

2.4 LOAD HANDLING TECHNIQUES

2.4.1 Classification Categories

The load handling operation is concerned with the correct placement of the load in the intra-plant transport system and the retrieval of the load from the transport system when the load has reached the correct destination. Within the field of load handling, three categories can be identified and these are listed in Table 2.2, together with some of the load transport mechanisms which use these

MANUFACTURER	TYPE OF AGV
Malthouse-Hunter Barrett	A, B, C
Jungheinrich	A, C, D
Wagner	A, B, C
BT Rolatruc	C, B
Komatsu	C
FATA (Carrago)	C
Digitron Eaton-Kenway	B
Babcock	B
Kings	B
ACS (Volvo)	B
NDC/Tellus	B
Sumitomo Corp.	A, B, C
Control Engineering	A
Clark	A, C
Clay Bernard	
The Raymond Corp.	B
Saab-Scania	100 ton mine dumper trucks [25]
Logisticon	D (bolt on unit for narrow aisle trucks)

A = Towtractor with trailers

B = Pallet truck

C = Fork lift truck

D = Order picker truck

TABLE 2.1 : MAJOR MANUFACTURERS OF AUTOMATED GUIDED VEHICLES

1. Slide On/Slide Off
   - A. Towtractor with trailer
   - B. Pallet truck
   - C. Pallet truck with chain or roller conveyor
   - D. Conveyor

2. Slide On/Off Plus Lift
   - A. Pallet truck with flat lift table
   - B. Fork lift truck

3. Order Picking
   - A. Order picker truck
   - B. Paternoster type systems

TABLE 2.2 : LOAD HANDLING METHODS AND MECHANISMS

techniques. In cases where the load is simply pushed from one mechanism to another, either manually or automatically, all that is required is a slide on/slide off capability and this is commonly used for pallet trucks and towtractors with trailers[19]. In cases where the load is picked up and deposited at static load stations a lift capability is also required and the automatic pallet trucks used in the slide on/slide off situation are often equiped with a lifting table[20]. Finally in situations where order picking is required a human operator normally does the picking after being correctly located by the order picking mechanism. This could be an order picking truck with either manual or automatic guidance to the correct bin location, or a paternoster type system in which the bin is brought to the order picker.

In all except the order picking case, the load is transferred to a load transport mechanism which can then take it to wherever the load is required in the plant. In the case of order picking, either the order picking truck, under manual control, can transport the load, or the picked items are combined with other picked items to form a load which can then be taken by one of the load transport methods mentioned in Section 2.3. The load is then ready to be transported to its destination.

2.4.2 Automatic Handling Methods

Of the three load handling categories outlined in the previous section, only the first two are used under automatic control with driverless vehicles. Earlier systems moved the vehicle or trailer adjacent to some pick-up and deposit (P and D) station such as the end of a conveyor and the load was simply pushed onto the vehicle, either manually or with the use of a hydraulic arm. A refinement of this system provided the transport unit with a chain or roller conveyor. This meant that with the simultaneous operation of the supply conveyor and the vehicle conveyor, the load could be moved onto the vehicle automatically. This system is used primarily with towtractors and trailers, although some pallet platforms do use the powered conveyor interface (Figure 2.3).

The pallet truck, however, is much more versatile when used with a lift table. With the provision of suitable slots in the P and D station (Figure 2.4), the pallet truck can drive underneath the station and pick-up or deposit a load by lifting its table. This allows it to interface not only with conveyor systems but also with fork lift trucks, narrow aisle cranes, automatic storage and retrieval systems (AS/RS), etc., through a non-powered P and D station which may be at the end of a conveyor or may be a stand alone station (Figure 2.5). This gives the pallet truck the ability to interface with any conventional materials handling system, thus giving it the flexibility of the fork lift truck. The advantage of this is that whilst the fork lift truck can only travel slowly in the reverse direction, the pallet truck, by virtue of its symmetry, can travel equally swiftly in either direction. The provision of a lift table thus gives the pallet truck an advantage over the automatic fork lift truck. The disadvantage is that it must be used with the P and D station. If the AGVS is being used as, say a link between stores and dispatch, this is no problem, but it is obviously unsuited to use in a warehouse, where the fork lift truck is in its element.

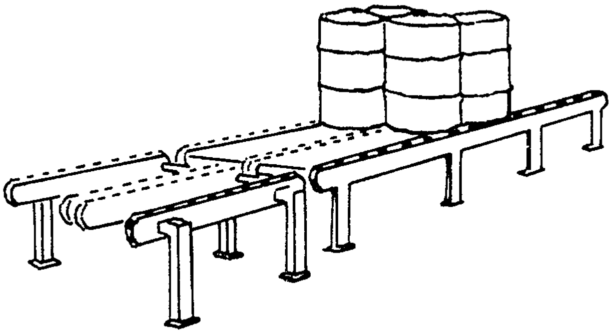


Figure 2.3 - Automatic Load Transfer Station
Powered Conveyor Interface

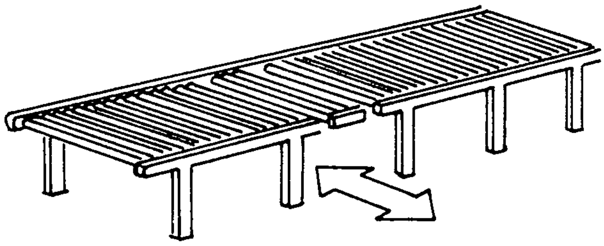


Figure 2.4 - Automatic Load Transfer Station
P & D Station Interface

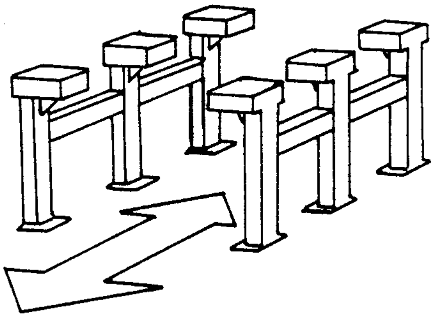


Figure 2.5 - Automatic Load Transfer Station
Stand Alone Station

The provision of automatic load transfer on automatic guided vehicles enables them to interface with AS/RS and other automatic manufacturing systems under the control of the system main computer. This offers the possibility of a completely automated operation and it is in this field that most of the development effort on AGVS is concentrated. However, as noted earlier, the need for the smaller, simpler system remains and it is only by the development of a more intelligent and more autonomous automatic vehicle that those systems can be fully satisfied. Such a vehicle would also fit into any larger system with the minimum disruption to the host system. This would provide the designers of materials handling systems with a much wider choice, for whereas at present the AGVS must be provided by the same supplier as the AS/RS or automatic warehouse, a more autonomous vehicle would enable the designers to pick the best AGVS to suit their materials handling framework. This would give much greater flexibility in the designing of fully integrated automatic materials handling systems, and thus allow more efficient and cost effective systems to be built.

2.5 INTEGRATED MATERIALS HANDLING SYSTEMS

The materials handling function, whilst fulfilling the same need in each industrial situation, varies widely in the details of its operation from one place to another. In a similar manner AGVS are employed in a wide variety of operations even though similar vehicles are being used to perform similar functions. There are many factors to consider when choosing a transport system[8,18], and an AGVS in particular[22,28]. Following Boldrin[4] we can establish a checklist of factors which together point to the requirement for an AGVS:

Labour saving potential

On-line material tracking required

Long transport distances involved

Interface with other automatic equipment

Clear gangways and production floor required

A large number of pick up and deposit stations

Medium level of activity

Loads misplaced or late in arriving

Loads are valuable and/or fragile

Three examples will be used to illustrate how AGVS perform within an integrated materials handling system. The first example is the glassworks of Heye in Obernkirchen, West Germany[23], where the AGVS interfaces at both ends of its operation with human operatives in the works. The second example is the new underground warehousing facility in Oslo[29,30]. Known as the Oslo Varedistribunal or OVD, it features a high degree of automation, and here the AGVS interfaces with human operatives on one side and an AS/RS on the other. In the final example, the Fiat Strada factories in Rivalta and Cassino[31], the AGVS interfaces with automatic equipment on both sides. On the one side it interfaces with automatic buffer stores, and on the other side with robot welders. The details given here for the three examples will only be those relevant to the AGVS operation, but fuller details of the three installations can be found in Appendix E.

2.5.1 Obernkirchen Glassworks

The Heye glassworks at Obernkirchen is one of the leading manufacturers of hollow glassware. One and a half million bottles are produced each day from 500 tons of vitreous glass, and this amounts to 700 palletised loads to be transported to store via an automatic covering machine and a shrinkage oven. Production is carried out round the clock on three shifts, seven days a week, without interruption. When looking at the transport system between production and storage, management wanted not only personnel reductions but also a system which could interface with the covering machine and shrinkage oven and had the flexibility to respond to organisational changes. For these reasons an automatic system was chosen. Because of the large load to be carried, towtractors each with three trailers were chosen, and fifteen machines were supplied by Wagner Indumat.

The operation is a fixed sequence of events and a minimum amount of automation is needed to run the AGVS. The central control merely allocates trucks when requested and monitors which trucks are operational and which are free. The system timing is controlled by manual inputs and the interface between the AGVS and the production and warehousing functions is under manual control. It is a simple yet very effective example of the use of an AGVS to cut operating costs. The use of the AGVS, whilst ensuring a 24 hour, 7 day operation has enabled sixteen people to be redeployed, and it has also speeded up the material flow.

2.5.2 Oslo Varedistribunal

The integrated warehousing, distribution and administration facility in Oslo, has been hailed as 'a new concept in total distribution'[30], and 'one of the most technically advanced (warehouses) in Europe, and certainly one of the biggest'[29]. The Oslo Varedistribunal, or OVD as it is known, is an underground public warehouse which is designed to relieve manufacturers of all the specialised management and supervisory chores, and of the capital burden of distributing their goods to the various points of sale. Built largely underground on the site of an old worked-out quarry in the suburb of Ulven in Oslo it features a high degree of automation. The 30,000 pallet high bay store has 24 automatic stacker cranes, and these are served by a fleet of 75 automatic vehicles. The cranes and the vehicles are supplied by BT. It is all under the control of two computers which besides controlling the equipment operation, also provide a full suite of stock control programmes including stock level control, real-time material tracking, customer and management status reports and the production of all the necessary paperwork. They also control lighting, heating, movement of personnel, monitor the 2,200 smoke, flash and flame detectors and control the network of 5,000 sprinklers. Again the AGVS provides a transport service from one location to another. However, the operation of the system is now under computer control and due to the much greater level of automation the human input is limited to instructing the system that there is a load to be stored or dispatched. The system features automatic loading and unloading at both ends of the AGVS operation and the slide on/off plus lift capability is provided by the automatic fork lift trucks. Accurate positioning of the load at the stacker crane P and D station is provided by floor mounted sensors. The computer systems consists of two computers. The Lager Administrativt System (LAS) computer controls warehouse stock and the Lager Styre System (LSS) computer controls the automatic systems. In comparing this system with the Obernkirchen system, two points can be made. One is that the large degree of automation has been made possible by the provision of an automatic load/unload facility on the AGV. The other is that this high level of automation requires two main line computers, 220 Megabits of storage and all the associated software to control it. This greatly increases the system complexity and hence its susceptibility to error.

2.5.3 Fiat Strada Rivalta and Cassino

In the Rivalta and Cassino plants, Fiat Strada car bodies are assembled on fully automatic lines. There are two automatic operations here; one for assembly of the side panels and one for assembly of the complete body. The Rivalta and Cassino plants produce 800 bodies per plant over two shifts. The handling system consists of 50 Digitron 'Robocarrier' pallet trucks per plant and the robot welders are Polar 6000, six axis NC machines. There are 88 of these robots in the two plants.

Here again the AGVS provides the transport service from one location to another and it is the automatic load/unload facility, this time provided by buffer stores, which allows for the large degree of automation. The computer control is effected by two PDP 11/70 computers with 430 digital inputs and 590 digital outputs.

It is the flexibility of the system which is the major advantage quoted by Fiat. Four different car models, which can be mixed randomly, can be accommodated on this one line without retooling. Conventional methods would demand multiple lines. Furthermore, the major system components, i.e. handling equipment, robot welders, computer and buffer stores, are non-specific and need not be changed to allow for new models. Only 30% of all components are specific to the model line and so retooling is not only swifter, but is also much cheaper than on conventional lines.

2.5.4 AGVS Operation with Integrated Systems

These examples show AGVS operating in very different systems yet performing very similar tasks. The only major difference between the AGVS in the three situations is the automatic load/unload facility provided by the fork lift truck in the OVD and by the buffer stores in the Fiat factories. Interfacing the AGVS with other automatic equipment greatly increases the computing power required and both the OVD and the Fiat systems require two large computers. However, most of this is likely to be for the other automatic systems. In Keebler's distribution centre in Alsip, Ilinois where an AGVS interfaces with an AS/RS, of the 48K of memory used only 10K was for the AGVS[6].

This leads many to believe that the automated vehicle is unimportant compared with total system considerations[21], and it is for this reason that most of the industrial research effort has been into improving the system performance and not the vehicle performance, as noted earlier. However, improvements in the vehicle performance are possible and these can lead not only to system improvements, but also to significant cost savings.

2.6 FUTURE DEVELOPMENTS

There are three main areas which will influence the development of automated systems in industrial environments. These are sensor technology, computer and microelectronics technology and changes in manufacturing ideas and methods.

(a) Sensor Technology

At present 2% of all factory jobs can be performed by robots. With the addition of some elementary sensory abilities this could increase to 35%[33]. Some observers put this figure as high as 65% to 75%[34]. Such an increase in automation would generate a further demand for automated transport systems to interface between materials stores and these robots. Thus, the AGVS would have to be able to position itself to robot tolerances (± 1mm) with a variety of robot types.

(b) Computer and Microelectronic Technology

The continued falling cost and increasing reliability of microelectronic and computer hardware makes their inclusion in systems more and more attractive. Furthermore, the increasing complexity and density of these components means that much more sophisticated systems can be implemented and this is aided by the development of associated software in many areas including automated scene analysis[28,35], artificial intelligence[28], vehicle control[36,37], warehouse and stock control[29,30], and control of automated machine and assembly lines[31,38]. This will enable more intelligent, environmentally aware systems to be developed which will have much greater flexibility and fault tolerance than present systems.

(c) Changes in Manufacturing Ideas and Methods

Important new ideas are now showing great impact on manufacturing methods and changing present ideas about production. The growth in the consumer society has led to a large increase in consumer products in all market sectors. It has also reduced the batch quantities of individual items[21]. The introduction of automatic manufacturing methods has led to an increase in production flexibility, allowing multiple product varieties to be produced on one machine line[31]. These two contributory factors have led to the emergence of a new production concept known as flexible manufacturing systems (FMS). FMS allow for low to medium production volumes of a large number of varying parts[20], thus allowing manufacturers enough flexibility to meet clients requirements in varying and unpredictable markets. In Japan where the FMS concept is most developed, robots are being operated on three shifts to make the relative cost of automation low enough[41]. The provision of an AGVS would allow for 24 hour, 7 day operation of these systems, economically mass producing batch items of one.

These ideas lead to the concept of an intelligent, autonomous automatic vehicle as the major component in a future, highly flexible

AGVS. The vehicle would feature an automatic load handling ability, a high speed of operation, an ability to recognise and manoeuvre in its local environment with knowledge of its wider environment for navigation purposes and enough sensory knowledge to enable it to operate safely and reliably in a variable environment. Much of the present research is aimed at providing an autonomous vehicle[28,35,39]. Following Norton-Wayne and Guentri[35] we can divide the work into hardware development and information analysis for guidance. CCD TV and framegraber techniques are advanced to a stage where most developmental effort is based on ways of extracting relevant guidance information from the sensory inputs. Paine[28] describes two instances where vehicles are guided from visual and sensory information alone, at JPL, Passadena and Stanford Research Institute. Both methods, however, use a large amount of sensory equipment which would not be feasible in industrial applications.

Methods using only a camera include using stereo images, colour images and time sequences of images. Norton-Wayne and Guentri[35] however use individual, monochromatic images. They have developed software for extracting boundaries and are working on methods of automatically identifying particular objects. This work is closer to industrial requirements and its completion should see automatic vehicles guided by visual information alone.

An alternative method using a lower level of computer control and more hardware is described by Marce et al[40]. Although the vehicle is not strictly autonomous, since three fixed beacons must be added to the environment, it does provide a free ranging vehicle with minimal disruption to the environment. The system has been operated successfully using only tactile obstacle detection. The provision of telemetry and remote obstacle detection would considerably speed up the vehicle.

Most of these systems use a large amount of highly developed, complex hardware. An alternative approach is to use less and lower technology hardware, and more sophisticated control techniques, such as state space representations and state observer systems. Using these techniques, Darenberg et al[37] reduced the sensory requirement of a wire guided bus from three sensors to one. This not only allows the use of cheaper, more robust sensors, but the necessary mathematical modelling of the system provides good portability of the system to other vehicles since the optimum system parameters are set in software.

The provision of a more flexible and robust vehicle within the AGVS at an acceptable cost will allow for greater use of automatic systems in manufacturing and warehousing.

2.7 SUMMARY

The use of automation offers industry a way to reduce costs and increase productivity, thus sharpening its competitive edge. In the field of materials handling, automation also brings the advantages of coherent handling schemes and swifter operation. The impact of automation on the materials handling field has been greatly increased by the emergence of automatic vehicles and automated guided vehicle systems. An important component of these systems is the automatic vehicle itself, and work to make it more intelligent and more autonomous would reduce the overall systems cost whilst simultaneously increasing the flexibility of the system.

ASTON UNIVERSITY

CHAPTER 3

THE RESEARCH PROGRAMME

3.1 OBJECTIVES

This Chapter looks in more depth at the research programme at Cableform Limited. A statement of the programme is followed by an examination of the system philosophy and then the translation of that philosophy into a practical system. This establishes the long term aim of the research programme. The techniques and expertise necessary to achieve that aim are then considered. The capability of the system to meet future developments in materials handling systems is investigated, and finally a justification of the research programme and its philosophy is given in the broadest of terms.

3.2 THE RESEARCH PROGRAMME

3.2.1 A Statement of the Programme

The aim of the research programme at Cableform is to develop a flexible automatic machine capable of performing a variety of load handling tasks which presently are performed by human operators. To achieve this end, the following target has been established: to develop a free-ranging vehicle which is guided through its environment without the aid of environmental markers and equiped with a highly flexible robot arm for load manipulation. It will use video pattern recognition techniques to extract real-time guidance information from a T.V. picture. Target information will be given in terms of video patterns, and cross correlation techniques will allow the vehicle to identify its destination. The robot arm, in conjunction with standard load handling equipment will provide the vehicle with an accurate, versatile load handling system allowing it to perform a wide variety of load handling operations which will include feeding CNC machines. Vehicle traction will be provided by an optimised drive system for a.c. motors. Such a vehicle could move freely and efficiently in any environment, and would find many applications in manufacturing and load handling situations, particularly in conjunction with other automatic equipment.

This is the envisaged development of this research programme. In view of the considerable amount of fundamental research which is needed to reach this goal, several development stages have been established which will allow the gradual development of the system. Figure 3.1 shows six vehicle control projects of increasing complexity which lead to the final system in a series of steps which are both technically feasible and commercially marketable. The advantage of this incremental development is the production of a family of mutually compatible control systems of increasing complexity. Thus, while the need for the simpler system is met by earlier projects, upgrading to more complex systems is facilitated by the common development base of these systems.

In an integrated AGVS installation two distinct control systems can be identified. One is the materials handling system which controls the movement of materials within the plant. The controller in this system is the computer in charge of the AGVS which receives commands from the resident stock and materials control system (manual or automatic) and actuates these instructions through the mechanism of the automated vehicles. The other control system is the individual vehicle in which the computer in control of the entire

DEVELOPMENT STAGE	LATERAL VEHICLE CONTROL	LONGITUDINAL VEHICLE CONTROL	LOAD HANDLING CONTROL	DRIVE TRAIN
1. MULTIPLE AGVS'S; CENTRAL CONTROL; AUTOMATIC LOAD / UNLOAD	WIRE GUIDANCE AND SOME SOFTWARE RESIDENT MANOEUVRES	LED ARRAY	LOADING MOTOR CONTROL	OPTIMISED D.C. MOTOR CONTROLLER
2. MULTIPLE AGVS'S; CENTRAL CONTROL; AUTOMATIC LOAD / UNLOAD; PLATFORM RAISE / LOWER	OPTICAL LINE FOLLOWING	CAMERA AND LOCATION MARKERS	LOAD SENSING 1-D LOAD POSITION SENSOR	OPTIMISED D.C. MOTOR CONTROLLER
3. MULTIPLE AGVS'S; CENTRAL CONTROL; AUTOMATIC LOAD / UNLOAD; PLATFORM MOVEMENT IN THREE PLANES TO HIGH PRECISION	DASHED LINES AND COMPLEX SOFTWARE RESIDENT MANOEUVRES	CAMERA AND SIGNPOSTS	3-D HIGH RESOLUTION LOAD POSITION SENSOR	OPTIMISED A.C. MOTOR CONTROLLER
4. POSITION DETERMINATION BY COMPARING VEHICLE POSITION WITH PREVIOUSLY LEARNT SURROUNDINGS	CAMERA PROVIDING ALL VEHICLE POSITIONAL INFORMATION. SOFTWARE CONTROLLED GUIDANCE WITH SOME ENVIRONMENTAL SIGNPOSTS		EDGE SENSING VISUAL AND TACTILE	OPTIMISED A.C. MOTOR CONTROLLER
5. DEVELOPMENT OF ROBOT ARM FIXED LOAD SHAPE	VIDEO PATTERN RECOGNITION TO REPLACE ENVIRONMENTAL SIGNPOSTS		ROBOTIC ARM, 3-D SENSOR FOR ARM	OPTIMISED A.C. MOTOR CONTROLLER
6. DEVELOPMENT OF ROBOT ARM VARIABLE LOAD SHAPE			VIDEO PATTERN RECOGNITION ORDER PICKING	OPTIMISED A.C. MOTOR CONTROLLER

FIGURE 3.1 : THE CABLEFORM AUTOMATED VEHICLE - DEVELOPMENT PROGRAMME

vehicle is the controller and there are various actuators in the form of the traction motors, the steering motor, etc.

Figure 3.2 shows the block diagram of an AGVS. The computer in charge of the AGVS is designated Group Control and it receives instructions from the plant through a main frame computer, in situations where some automation of materials movement already exists, and through manually operated 'work stations'. Group control optimises the running of the AGVS fleet and sends its instructions to the vehicles over a different communications link than that to the work stations and main frame computer. The microprocessor in charge of the vehicle is termed Vehicle Executive. The following system sub-projects can be identified:

(a) Group Control
(b) Communications
(c) Work Stations
(d) The Vehicle Executives

Figure 3.3 shows the block diagram of an automated vehicle. Vehicle Executive is in charge of the whole vehicle and controls a number of vehicle functions which are shown beneath it. These functions are all individually controlled by microprocessors which normally operate autonomously, except when information transfer between the sub-system processor and Vehicle Executive is required. This transfer is always initiated by Vehicle Executive which interrupts the sub-system processor and either requests or transmits information. If the sub-system processors wish to communicate with Vehicle Executive, they do this by interrupting Vehicle Executive and requesting communications.

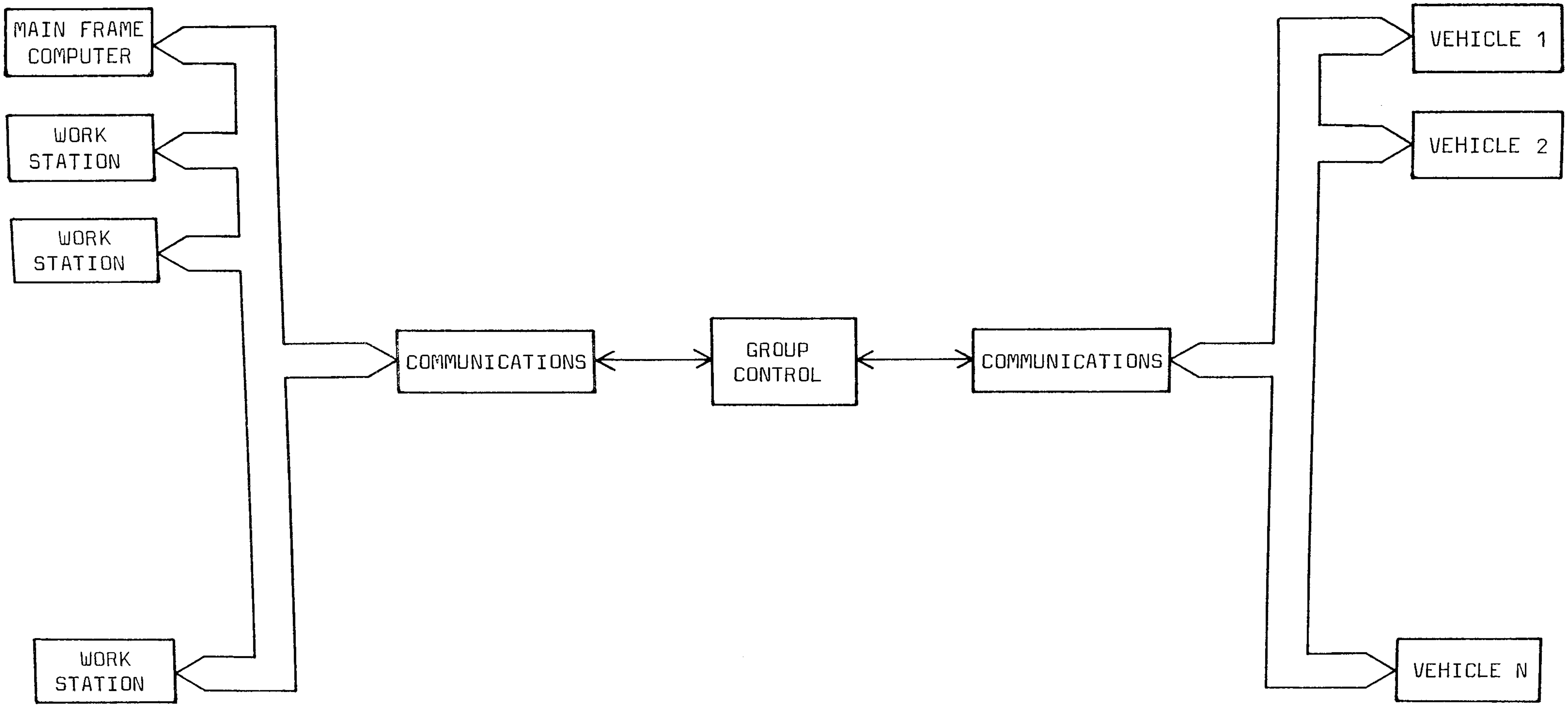


FIGURE 3.2 : BLOCK DIAGRAM OF AN AGVS

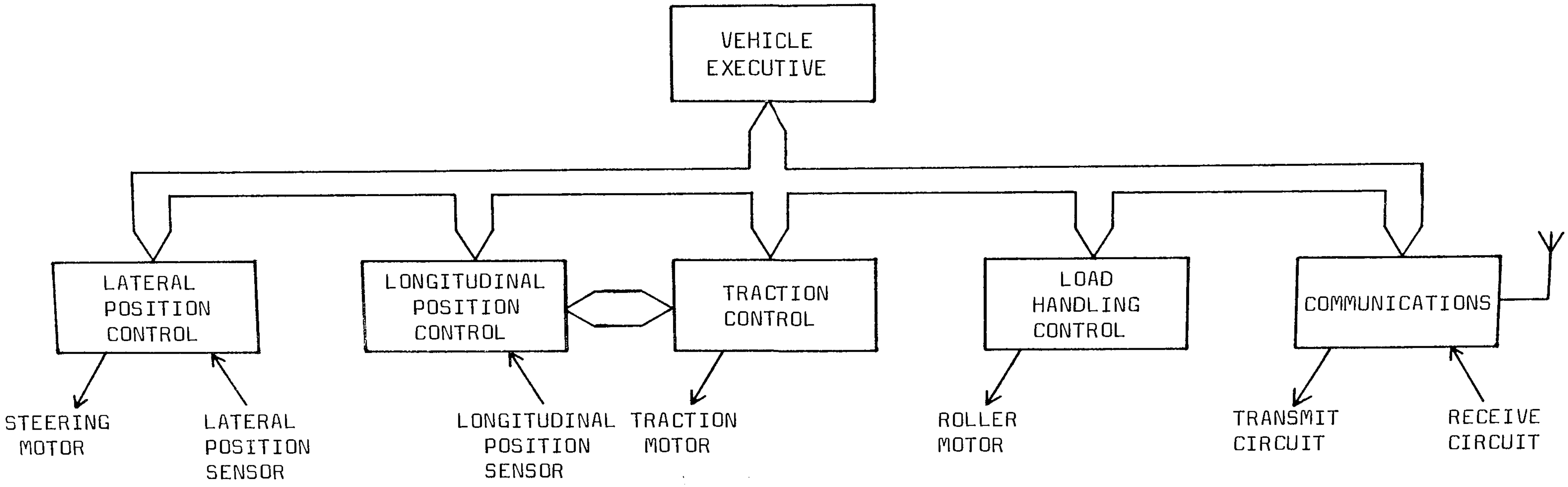


FIGURE 3.3 : BLOCK DIAGRAM OF AN AUTOMATED VEHICLE

This done, however, they must then return to their quiescent condition and wait for Vehicle Executive to interrupt them and request information. Sub-system processors would request communications in situations such as loss of guidance control, receipt of group command signals, flat battery condition, position recognised, etc. The following vehicle sub-projects can be identified:

(d) Vehicle Executive
(e) Lateral Position Control
(f) Longitudinal Position Control
(g) Traction Control
(h) Load Handling Control

and the vehicle communications is included in system sub-project b. Sub-project d has been included in both lists since it is an important part of both systems. Vehicle Executive sits between Group Control and the actual operation of the vehicle electronics and hardware, and translates the high-level system commands of Group Control into lower-level functional commands to the vehicle microprocessors. In the materials handling system the Vehicle Executives are the controlled machinery since it is their operation which carry out the system commands. In the vehicle system the Vehicle Executive is the controller which issues the system commands, albeit in response to instructions from Group Control.

The project which is presently under development is the first of the six projects. This calls for multiple vehicles under central control with an automatic load/unload facility. System control is achieved by a centralised Group Control and on-board Vehicle Executives. Group Control receives basic fetch and carry commands from the host computer and the work stations. It then optimises vehicle use and prepares command lists for each vehicle. It monitors the positions of all the vehicles under its control. Vehicle routes are planned by the individual executives but route clearance and traffic control at crossroads and junctions is provided by Group Control. It then transmits the movement instructions to the individual Vehicle Executives.

The Vehicle Executive receives commands from Group Control and expands them into an agenda of functional commands which it communicates to the vehicle processors which translate them into machine commands and execute them. Lateral position control is by wire guidance and longitudinal position control is achieved by environmental markers together with a vehicle mounted array of light emitting diodes and photo detectors. Loading and unloading is provided by powered rollers. The drive train is an armature controlled, separately excited d.c. motor with a constant field.

The developmental timescale of project one is given in Figure 3.4 and shows that this stage should be completed by the fourth quarter of 1982.

THE CABLEFORM AUTOMATED VEHICLE PROGRAMME

PROJECT NUMBER : ONE

PROJECT DESCRIPTION : MULTIPLE VEHICLES; CENTRAL CONTROL; AUTOMATIC LOAD / UNLOAD

SUB-PROJECT	1980				1981				1982			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
GROUP CONTROL											■	■
COMMUNICATIONS										■	■	■
WORK STATIONS											■	■
VEHICLE EXECUTIVE									■	■	■	■
LATERAL POSITION CONTROL				■	■	■	■	■	■	■		
LONGITUDINAL POSITION CONTROL				■	■	■	■	■	■	■		
TRACTION CONTROL									■	■		
LOAD HANDLING CONTROL								■	■	■	■	

FIGURE 3.4 : THE TIMESCALE OF DEVELOPMENT FOR PROJECT ONE

3.2.2 The System Philosophy

The preceding section describes the aim of the research programme and the individual projects which together constitute the whole programme. It was noted in Chapter 1 that the corporate philosophy of the Company requires that these control systems be independent of the vehicles to which they will be fitted. Two other important factors which can be identified are that the vehicles must work and communicate in potentially noisy electrical environments and hence must show good noise immunity, and that the six projects all perform the same job only at different levels of complexity and so to provide for ease of upgrading, the modular units of the systems must be compatible throughout all six projects. These requirements give rise to a design philosophy based on three fundamental concepts:

(a) Delegated Intelligence
(b) Mathematical Modelling
(c) Software Based Parameters

How these principles meet the above requirements of the system will now be considered.

(a) Delegated Intelligence

The requirement for vehicle independence is an application of the concept of transparency as met in multi-processor systems generally[49]. This concept can be explained as follows: The Group Control issues a command to take a load from position m and place it in stock location n. The vehicle which receives the command moves the load and then instructs Group Control that it has done so. If the vehicle is changed for one of a different design which can nevertheless perform this same function then Group Control will still issue the same command and receive the same task complete message. Thus, Group Control issue a command, and 'sees' it executed without 'seeing' the form of the vehicle which actually executes the command. Thus, the vehicle is transparent to the Group Control, and any vehicle which can physically perform the task can be used, without Group Control needing to know what sort of vehicle it is. This means that Group Control can be designed and built without needing to know anything about the vehicles which it will be controlling. This is only possible because the vehicle itself is intelligent. It can receive a command to move a load from one location to another and turn that high level functional command into the machine operations necessary to complete the task. Thus, the concentration of intelligence in the vehicles gives Group Control vehicle independence.

In the same way, the use of microprocessors to control each of the vehicle functions means that the vehicle hardware is transparent to the Vehicle Executive. The commands that Vehicle Executive receives from Group Control are highly functional in nature. Vehicle Executive reduces these commands to a series of lower level commands which it communicates to the individual vehicle processors. Although of a lower level than the Group Control commands, these commands are still functional in nature and may be of the form, 'drive at 50% duty cycle in the forward direction', to traction control, or 'stop at marker three', to longitudinal position control. It is then the individual processors which translate these functional commands into actual machine operations. Thus, the form of the hardware, both the vehicle and its control system, is transparent to the Vehicle Executive, and so Vehicle Executive can be designed and built without knowledge of the vehicle it is controlling. A change in hardware, a new traction motor controller say, would entail changes to the traction control software and wiring harness, but the traction control processor would still receive the same command to drive the vehicle forward at half power, and the Vehicle Executive would still 'see' the vehicle move forward at half speed. Again this independence of Vehicle Executive from the vehicle it is controlling is only made possible by the delegation of intelligence into the processors controlling each individual vehicle function. Thus, the concept of delegated intelligence means that vehicle and control system hardware only becomes important at the level of vehicle sub-system, and then only to those processors which actually see the hardware (i.e. a change of traction motor controller will not affect the communications sub-system).

There is, in addition, another major feature of delegated intelligence. Since the commands that are issued are all functional in nature, the time spent in sending these commands is much lower than if the same command was issued in machine operation form. This considerably eases the communications problem. In the communications link between Group Control and the Vehicle Executive, this low information content means that low baud rates can be used, and this improves the noise immunity of the link. Thus, information integrity can be maintained even in noisy environments. In the communications link between Vehicle Executive and the individual vehicle processors, this low information content means that the time spent in communicating can be kept very low. This has two advantages. Firstly, since only one sub-system processor can communicate with Vehicle Executive at any one time, short communication times will ease the problems of contention when more than one processor wishes to communicate. Secondly, the short communication times mean that the sub-system processors do not spend large amounts of time communicating, to the neglect of their own function. This eases the problem of communicating whilst maintaining the real-time operation of the vehicle function, and means that the vehicle will not crash because it was too busy talking!

Thus, the use of delegated intelligence leads to a series of well defined units whose interface protocols are fully specified; this is simply another expression of the concept of modularity and means that the input requirements from the various sensors is fixed.

Fixing the sensor input requirements ensures the interchangeability of the sub-systems from different projects, for despite hardware differences the more complex sensors will still be required to present the same input profile as the simpler sensors. Thus, for example the guidance system from project one, which requires two coils, a guide wire and a wheel angle potentiometer, can be directly replaced by the guidance system from project six, which requires a TV camera and sophisticated pattern recognition and path generating software. In making this change there is no difference to the Vehicle Executive whose command to steer the vehicle from position m to stock location n is met by both systems. Thus, the modularity concept ensures hardware independence to all the system modules except that one which controls the piece of hardware concerned. It also leads to short communication times and so enables the system to operate in noisy environments.

(b) Mathematical Modelling

The system modules which actually control the hardware are the only parts of the system which actually 'see' the equipment. Thus, they are the only parts of the system to be affected if the hardware is altered. The use of a mathematical model enables the effect of any changes to be identified *a priori* . Then the vehicle sub-systems can be designed so as to minimise the alterations that need to be made to the sub-system controllers so as to allow them to operate with a wide range of equipment. Thus, although the vehicle sub-systems are not entirely hardware independent, the changes that need to be made can be minimised.

(c) Software Based Parameters

The use of a microprocessor as the sub-system controller means that those elements of the controller which must be altered to match hardware changes can be held in software. This means that the control system can be made to suit any vehicle type simply by a software change. Furthermore, once the model of the vehicle and control hardware has been developed and established, system improvement lies solely in sensor development and will be rapid.

Thus, the use of digital techniques and mathematical models means that vehicle independence is extended to the point where any change of vehicle or control hardware can be met simply by a software change and ensures the interchangeability of the control systems from different projects, thus allowing easy upgrading of installed systems.

3.2.3 The Functional Operation of the System Components

The use of a distributed intelligence system leads to the establishment of functional sub-systems whose operation must be clearly defined to allow for hardware transparency and all the benefits of vehicle independence and modular interchangeability. The eight vehicle sub-projects identified earlier are defined throughout the entire development programme of six projects. With the increasing complexity represented by each new project the function of each of these sub-projects will not change. Rather the functions will be performed more efficiently, with less need to alter the environment, and with a greater range of possible operations. The functional operation of the eight sub-projects will now be described. Any hardware descriptions apply to project one and are included simply to fix ideas on the functional operation.

(a) Group Control

Group control is responsible for the running of the AGVS which it does in response to instructions from the mainframe host computer and the work stations. Instructions will be of two kinds; requests for information which permit the operator to find out the location and level of stock holding, and commands which detail the movement of stock. When commanded to move stock, Group Control will first look at its stock lists (taking due regard of stock rotation) to find out where the items are located. It will then instruct the first 'free' vehicle to carry out the task. 'Free' can be defined on a sequential basis in which case all vehicles are operated to the same extent, or it may be defined according to a priority listing which performs differential operation of vehicles, thus using newer trucks more than older ones. If there is no free vehicle then Group Control will wait for the most suitable vehicle to come free. Suitability will depend on the length of each vehicle's present task, the vehicle priority list and the geographical location of each vehicle on completion of its present task. If there is a list of tasks and no vehicles free to do them, then Group Control will work out an agenda for each vehicle such that the tasks are carried out in the most efficient manner, and vehicle movements are optimised.

The routes taken by the vehicles are worked out by their own executives, but each executive must request permission from Group Control before embarking on a particular stage of a journey. Once a vehicle has been granted priority at a junction, then Group Control will prohibit all the other vehicles from using that junction until it has been cleared.

Thus, it can be seen that Group Control has two main tasks:

(a) Stock Control

(b) Traffic Control

Furthermore, as may be seen from Figure 3.2, Group Control is at the heart of the materials handling system and is hence the component most sensitive to error and failure. A malfunction in Group Control could lead to complete system shutdown. The Group Control function will therefore be carried out by two identical but entirely independent units, each of which is capable of carrying out the Group Control function in isolation, though perhaps at reduced speed. In normal operation one will perform the stock control function and the other will perform the traffic control function. In the case of a catastrophic fault condition in one unit, the other unit will take over the operation of the neglected function. This will allow the materials handling system to continue operation despite the breakdown of one unit, and it also means that equipment maintenance can be carried out without the need for a system shutdown. Indeed, if maintenance periods are chosen during quiet periods in the system operation, much regular maintenance can be carried out with no effect on the system operation at all.

(b) Communications

There are three major communications networks in the materials handling and vehicle system. The first is the communication network between Group Control and the host computer and work stations. The second is the communications network between Group Control and the vehicles. The third is the intra-vehicle network.

Figure 3.2 shows that next to Group Control, communications networks one and two are the most critical parts of the system. This defines the need for systems with high information integrity and very low error rates. In the case of network one which is a connection between static units, multiway screened cable can be used to provide both high data rates and message security. In the case of the workstations this high data rate is not needed since the information content of any message they may send is minimal because of the functional nature of those messages. For Group Control, however, in view of the large amount of data which must be passed over to the host computer if a stock check is requested, the high data rate will ensure that Group Control does not spend too much time communicating, to the detriment of the AGVS operation.

Network two, requiring connections between mobile units, is provided by an F.M. radio link. This allows the vehicles to move freely within the installation without the risk of losing contact with Group Control. Since any industrial environment presents a lot of electromagnetic noise to a communications system, noise immunity will be a major problem. However, by the use of low baud rates, multiple broadcasts of a single message and suitable software parity checks in the receiving unit, acceptable error rates can be achieved.

Network three is the intra-vehicle communications link. All sub-systems have a communications port which are all interconnected on a common data bus to the communications port on the Vehicle Executive. It is important to realise that the communications sub-system does not control intra-vehicle communications but rather the link from the vehicle to Group Control (i.e. network two). If Vehicle Executive wishes to send a message to Group Control then it sends the information to the communications processor on network three and leaves the sub-system to transmit the message to Group Control over network two. Network three is controlled by the Vehicle Executive. If it wishes to communicate with a sub-system, it sends an interrupt request to the relevant processor. This interrupt has the highest priority in the sub-system and will always be recognised as quickly as possible. On acknowledgement of the interrupt request the sub-system processor will decode the communications control word which has been placed on the data bus by Vehicle Executive. This will tell it whether to transmit or receive information. The processor will perform the required operation and then return to its normal operating mode. If a sub-system wishes to communicate with the Vehicle Executive then it must send an interrupt to Vehicle Executive and place a communications control word on the data bus which will identify the interrupting processor. On acknowledgement of the interrupt by Vehicle Executive, the interrupting processor will return to its normal operating mode. It will then be interrupted by Vehicle Executive with a request for information according to the protocol above. Situations where sub-system processors would ask for communications would be: the communications processor on receipt of a message from Group Control; the steering processor on loss of guidance; the longitudinal position control processor on identification of a stop marker, etc. The intra-vehicle communications protocol is given in Appendix C.

Networks one and three, by the nature of their connections can be made tolerably noise immune. A fault in either of these networks would affect only the faulty unit and while reducing system capacity it would not completely shut down the system. Network two is the most sensitive part of the communications system and must be designed to give the total system good noise immunity and fault tolerance in potentially noisy environments.

(c) Workstations

Workstations are limited system peripherals which allow an operational level of interface to the AGVS, i.e. it does not permit access to management information such as stock checks and vehicle availability but does allow the transfer of those movement orders and requests for information which are necessary for the operation of the total materials handling system. Thus, the movement orders will be of a simple format, specifying:

(a) What is to be moved (reference).
(b) How much is to be moved (quantity).
(c) Where it is to be moved from (collection).
(d) Where it is to be moved to (destination).

There will also be instructions which will enable the workstation to quiz Group Control on such matters as stock availability and where a particular item is held in the store, thus enabling normal warehousing operations to be carried out.

The workstation will normally be a standard peripheral terminal (e.g. VDU, teletype, etc.) operating on semi-customised software.

(d) Vehicle Executive

The Vehicle Executive is responsible for the running of the individual automated vehicle. It receives high level functional commands from Group Control and plans an agenda of vehicle actions suitable for performing the requested task. It contains its own map of the operating environment and can thus plan its own routes, but it must obtain route clearance from Group Control before embarking on a journey.

There are two main functions of the Vehicle Executive. On the one side it communicates with Group Control and is the controlled machinery in that control system. It receives commands from Group Control and provides Group Control with information about how its task is proceeding and the state of the materials handling system, i.e. location and level of stock. In this role, the Vehicle Executive is a slave system and operates only on commands from Group Control. On the other side, Vehicle Executive is the unit in charge of the whole vehicle. Having received a command from Group Control, Vehicle Executive will translate this into an agenda of vehicle actions and send these out to the vehicle sub-systems. Thus, Vehicle Executive is the master system in charge of several intelligent yet nevertheless slave sub-systems.

(e) Lateral Position Control

The lateral position control system is the most autonomous of all the vehicle sub-systems, since it can continue operating at all times and regardless of vehicle situation with no adverse effect to the operation of the whole vehicle. Furthermore, a fault condition in this system, which represents a loss of steering, is so grave an error, that the vehicle must halt immediately and this is done directly by the steering sub-system without referring to Vehicle Executive.

There are three modes of operation of the steering sub-system: automatic, manual and slave. In the automatic mode, the system sets the wheels at an angle dictated by the steering sensor and only communicates with Vehicle Executive when asked for information or if a fault arises. It continually re-triggers a monostable which keeps a relay closed. If the steering processor should lock-up then the monostable would no longer be retriggered and the relay would open. This operates the main power line contactor, thus shutting off all vehicle control hardware and applying electromagnetic brakes. Thus, should the steering system cease working, the vehicle will halt. The system also continually monitors the signal level in the guidance sensor. If it falls below a certain threshold level then the processor informs Vehicle Executive of the loss of guidance signal, leaving Vehicle Executive to decide if this is problem or not. This is the only situation under automatic control in which the steering sub-system initiates communications with Vehicle Executive.

In the manual mode a remote control box is plugged into the vehicle. The presence of the plug from the control box in the socket tells the steering sub-system that manual control is required. Initially this control box will provide only steering and traction information, but later versions will be able to control other vehicle functions too. When the steering processor notices that manual operation is required, it informs Vehicle Executive and then reads in steering and traction information. It sets the steering wheels according to the steering information received and stores the traction information ready for transmitting to Vehicle Executive which takes the responsibility of passing over the information to traction control by asking the steering sub-system for the relevant data. All the time while in manual control the processor continually re-triggers the monostable irrespective of the steering sensor signal level, thus maintaining vehicle operation even while not on the wire.

The slave mode of system operation is a slight variation on the automatic mode. When in automatic operation, Vehicle Executive can override the steering information provided by the steering sensor and substitute its own information. This allows software controlled manoeuvres to be carried out and this can considerably simplify some of the problems encountered with wire guidance systems. For example, in enclosed areas where it is difficult to lay a wire, the vehicle can be operated, off the wire under software control. Also it can simplify the procedure at crossroad junctions. Most present systems use a four-delta shape of crossroad and a multi-frequency system with switching gear on the vehicle. This needs six frequencies for a single crossroads (see Figure 3.5) and leads over a complete installation to systems with seven frequencies[50]. The software controlled manoeuvre facility eliminates the need for the delta shapes and multiple frequencies. On approaching a crossroad, Vehicle Executive instructs the steering processor to ignore the steering sensor and set an angle which will take it round the corner (position 1, Figure 3.6). As the vehicle leaves the wire, the steering processor notes the loss of guidance signal, but does not shut down vehicle operation because of the software override (position 2). Vehicle Executive then merely instructs the steering processor to maintain that angle until it picks up the guidance signal again

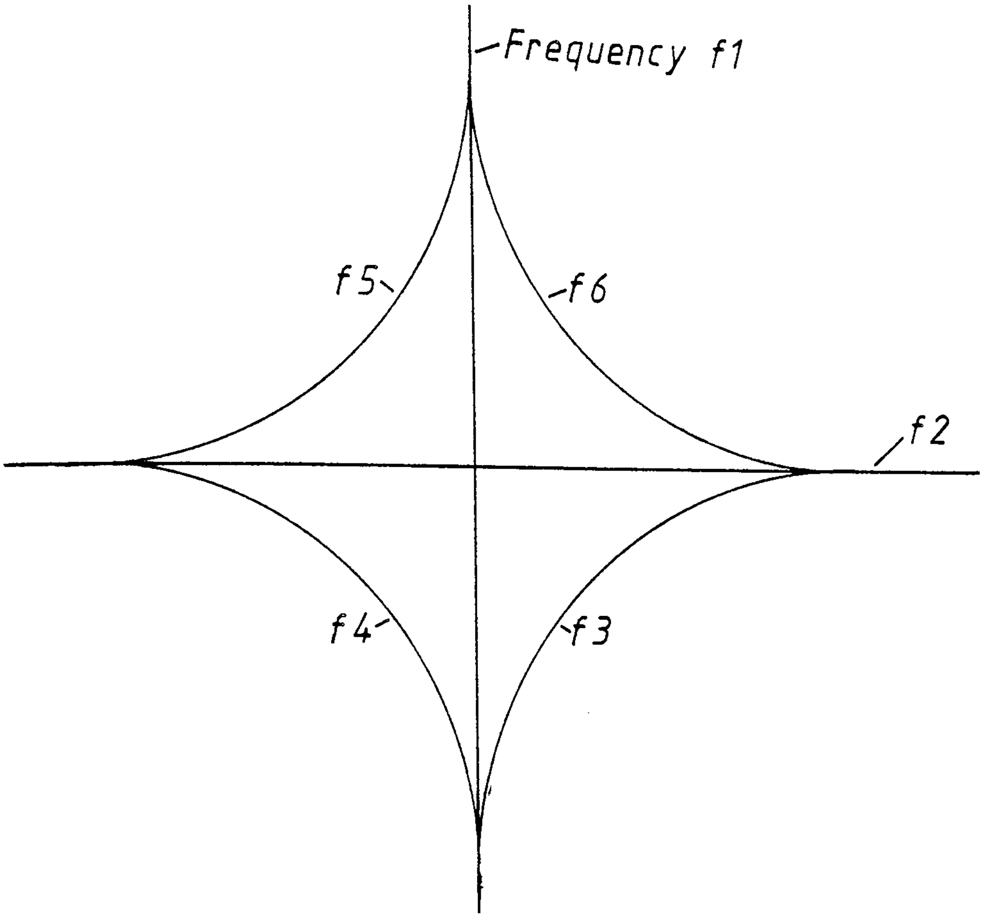


FIGURE 3.5 : PRESENT CROSSROAD GEOMETRIES

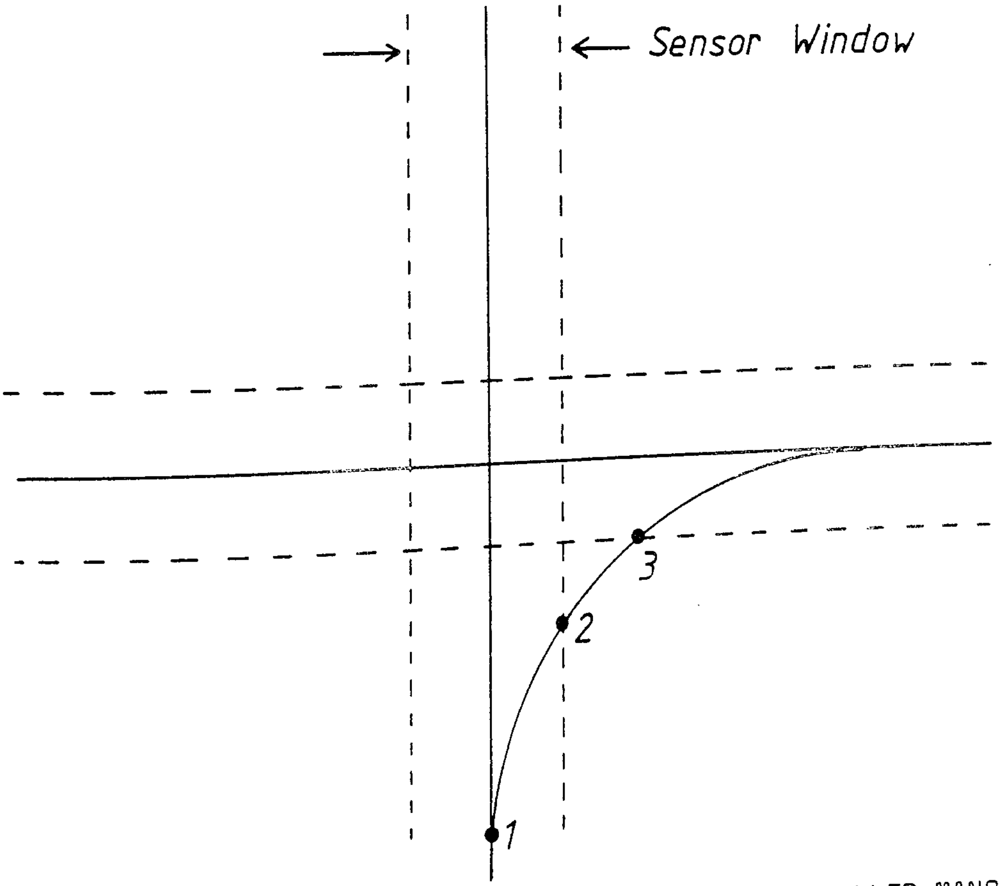


FIGURE 3.6 : CROSSROAD GEOMETRY WITH SOFTWARE CONTROLLED MANOEUVRES

(position 3), at which point it may return to the fully automatic mode of guidance. This facility not only simplifies the design of the materials handling system by limiting it to a single frequency and hence reduces its cost, but it also simplifies the installation of the guide wire by dispensing with the four-delta shape of crossroad. This means that physically less wire is used and it does not take as long to install, both of which mean that it is cheaper to install the system.

(f) Longitudinal Position Control

The vehicle is constrained to follow the guidance route by lateral position control, while options along the route are handled in Vehicle Executive by the use of a software steering override. All that is then required for complete automatic guidance is the monitoring and accurate positioning of the vehicle along the system layout, and this is done by longitudinal position control. Along the guidance route are scenes which the longitudinal position control can recognise. These take the form of either guidance markers at crossroads and junctions, or position markers at required stopping places. The form of these recognisable scenes will vary from dedicated markers specially located in the environment in project one to the normal video pattern of the scene which is already held in the processor memory in project six. But however achieved, these recognisable scenes will provide longitudinal position control with the knowledge of where the vehicle is on the system guidance route. In the case of guidance markers, the longitudinal position control system will merely pass the information over to Vehicle Executive so that it knows where the vehicle is, and can make any decisions connected with vehicle position, e.g. steering override, vehicle halt, etc. When the system identifies a position marker it will first check to see whether it has been requested to stop at this marker. If it hasn't then it will simply inform Vehicle Executive of where it is in the same way as it does with a guidance marker. If, however, it has been requested to stop, then longitudinal position control will inform Vehicle Executive of the need to stop, and Vehicle Executive which normally supplies traction control with information, will allow longitudinal position control to take over the running of traction control directly. This is the only case in which one sub-system processor directly controls another. Traction is put into a creep speed and then following the signals from the recognised scene, the longitudinal position control accurately aligns the vehicle to the scene. When in position, at which time the traction motors will necessarily be stopped, longitudinal position control informs Vehicle Executive that the vehicle is in position and returns traction control to the Vehicle Executive.

(g) Traction Control

Traction control drives the vehicle according to its received instructions concerning speed and direction. Normally it receives its instructions from Vehicle Executive, but when approaching a position at which the vehicle is required to stop, longitudinal position control will provide it with instructions.

The use of a separate processor gives hardware transparency to the actual drive motors and allows the use of closed loop speed control which overcomes the irregularities introduced by surface and gradient variations. It will also allow the processor to recognise faults such as oil on the floor which would be characterised by an excessive velocity on one of the drive wheels.

(h) Load Handling Control

Load handling control is responsible for the operation of all load handling equipment on the vehicle. Since this function is dormant during vehicle movement it is also responsible for the operation of obstacle monitors and other vehicle safety equipment during traction. Long range obstacle detectors are provided by ultrasonic sensors, and these are also used for positioning the load handling equipment when transferring material. Tactile sensors are also provided as an emergency backup. When the vehicle is moving the load handling processor operates the safety equipment and informs Vehicle Executive of any problems. When the vehicle is engaged in materials movement, the processor checks the alignment of the vehicle and load station. This position check is not as accurate as longitudinal position control, but provides a safety check on the correct operation of that processor. Load handling then checks that the vehicle is not moving and applies the electromagnetic brakes if they have not already been applied. Only then can it transfer a load. The load position sensors inform load handling when the load is correctly aligned, i.e. completely off the vehicle, or properly on it, and it can then release the electromagnetic brakes. It then informs Vehicle Executive that load transfer is complete and can also advise at this time of any speed restriction on account of the weight of the load. It then returns to the operation of the vehicle safety equipment, until the next materials handling situation is reached.

This functional description gives the tasks that each sub-system processor is required to perform. This is independent of whatever control systems may be on the vehicle and as such is defined throughout all six projects of the research programme.

3.3 METHODOLOGIES

When the research department was set up early in 1979, very little expertise was available on the sort of problems which the automatic control of a battery electric vehicle would present. Cableform's motor controllers, although excellent in their own field, are open loop controllers whereas automatic control of any system by its very nature demands closed loop control. The use of microprocessors for engineering purposes within the company was only just starting and so as yet no expertise was available in that area. Experience in mathematical modelling in the company was limited to the steady state performance of motors; there was no knowledge of motor transients and vehicle kinematics. Thus, much of the early work of the department was in establishing the research programme outlined earlier, and finding what expertise was needed in order to pursue that programme.

Three main areas of expertise can be identified, and these are:

(a) Control Theory.
(b) Microprocessors and Digital Techniques.
(c) Mathematical Modelling Techniques.

Control Theory

The automatic control of any machinery must involve the setting of the controlled machinery according to some reference or datum. In a manually driven battery electric vehicle it is sufficient to provide open loop control systems since the driver himself can close the loop to provide the required vehicle control. Indeed, the driver performs the function of closed loop controller for several control loops and thus represents an incredibly complex controller. In an automatic vehicle, however, the controllers must all be closed loop. Thus, the research department must have a very good practical knowledge of control theory. Furthermore, the systems will be subject to non-linear and even in some situations time-varying variables. Thus, closed loop systems are even more important to minimise the effect of these disturbances, and the department's practical knowledge must include techniques for dealing with such disturbances.

Microprocessors and Digital Techniques

The use of microprocessors in the department is essential for two main purposes. One is the development of the mathematical models, and the other is for controlling the vehicle hardware. It is only by using microprocessors that the required portability or vehicle independence can be achieved. Thus, the department needs familiarity not only with the hardware aspects of digital control, but also with the software techniques. It is an interesting point that the control of battery electric vehicles is ideally suited to digital techniques. The proportional control of a battery supply requires chopping of the full battery volts according to some duty cycle to provide the proportional voltage required, and the duty cycle is easily provided by the two discrete levels of a digital bit. This gives rise to the need for power circuits which take the 0 to 5 volt variation of a digital bit and turn it into full battery volts variation at high current, and these have all been developed in the research department.

Mathematical Modelling Techniques

The use of microprocessors in the control loops means that the system parameters which affect the loop operation can be held in software. This allows the systems to be adapted to different vehicles by simple software changes. However, the variation of these parameters will affect the performance of the closed loop controllers, and could in extreme cases even result in instability. Thus, parameter variations must be met by other system changes such as gain or feedback variations. In order to understand how parameter variations affect the operation of the closed loop and the form of any compensation or variation which may be necessary to meet these changes, mathematical models are developed for each separate control loop. The mathematical model has many uses: it identifies the important system parameters; it shows which setting of system control parameters gives the best system performance; and it identifies the important parameters of the control hardware so that the best control can be realised, i.e. the motor constant directly sets the steering system bandwidth, and so for swift operation of the steering a motor with a large constant is required (see Section 5.2).

Establishment of expertise is never a swift process, and it has taken some time for the department to acquire these skills. Indeed the learning process never finishes and areas of obvious need for improvement can still be recognised, but the problems of the department today tend in the main to be manpower problems rather than lack of expertise. Increasing experience with the methods and techniques described above has enabled work to begin on the first of the six projects. Following the top-down design principle of this system, the development is from the bottom upwards. Accordingly, the first step is to build a single vehicle with minimal Vehicle Executive control, but with all the vehicle sub-systems. This allows the system to slowly develop in complexity while finding all the developmental problems at the earliest, and therefore cheapest, stage. At present then, work is proceeding on the establishment of the vehicle sub-systems on a single research vehicle. No work has been done on sub-projects relating to the complete materials handling system, i.e. sub-projects one and three and communications network one. However, these are standard applications of present technology and should present no fundamental problems on their introduction to the system.

3.4 FUTURE SYSTEM DEVELOPMENT

The most influential factor in future developments of materials handling systems as outlined earlier will be the growth of CNC machines. Their effect is twofold. Firstly, the inclusion of such machines in present manufacturing systems will give rise to the requirement for materials handling systems to position their loads to within robot tolerances. Secondly, the availability of such machines will lead to a growth in Flexible Manufacturing Systems. This will demand not only a Flexible Materials Handling System but also a system with enough intelligence to locate loads in the correct orientation. Thus, the requirement will be for a flexible materials handling system which can locate loads accurately to robot tolerances in the correct orientation. The features necessary in such a system would be:

(a) Central control of multiple vehicles but independent (i.e. autonomous) operation of the vehicle in case of Group Control failure (and also to allow for the simple installation).

(b) Automatic load/unload capability to robot tolerances with shape recognition.

(c) Simple installation and extension of the system by the user. Extension to cover route changes, changes in the number and type of vehicles, changes in the number of P and D stations, changes in the operating area, changes to the environment, etc.

(d) System based on digital techniques for high reliability and low maintenance.

(e) Modular design to allow for ease of upgrading or expanding the system.

(f) Speed continuously controllable from a high speed of 3 mS^{-1} to a creep speed of 0.1 mS^{-1}. High cruising speed reduces the cycle time and hence the number of vehicles needed. Speed control is essential for tight corners. Creep speed is essential for accurate positioning to robot tolerances (1mm).

(g) Multiple Safety Features. Sophisticated microprocessor controlled safety equipment must be backed up by simpler electronic and mechanical safety equipment so that safe operation is guaranteed at all times.

The development programme for the Cableform automated robot vehicle is shown in Figure 3.1, and it can be seen how the long term development, represented by project six would meet all these requirements. Guidance by video pattern techniques would mean that the system could be installed merely by placing the video pattern of natural landmarks in the vehicle memory. Any changes to the environment, route extensions, etc. could be met by placing the new video patterns in memory. Vehicles can manoeuvre independently of Group Control and a manually operated radio unit would mean that the system could still operate even if Group Control failed. The robot arm would allow the feeding of CNC machines with parts in the correct position and orientation. Standard load handling equipment would permit the normal movement of goods and when used in conjunction with the robot arm, even order picking could be achieved. Furthermore, the flexibility of the system means that it could easily interface with present materials handling equipment and could even operate as a stand alone materials transport system for the simpler, small scale operation. Thus the proposed system will meet the expected future demands on materials handling systems.

With regard to the lateral position control of the vehicle, the following development of guidance control can be established:

(a) Path immediately sensed (e.g. wire guidance, white line following, etc.).

(b) Path immediately sensed plus simple software controlled manoeuvres.

(c) Software controlled guidance with environmental signposts and a software resident map.

(d) Software controlled guidance with path generation from video data.

These four development stages, spread over the six projects, form a logical sequence in the move to put less and less structure on the environment for guidance purposes by putting more and more intelligence into the lateral position control sub-system. It is designed to take advantage of the increasing complexity, density and speed of microcomputer components which along with their decreasing cost is expected to continue through the next decade.

3.5 JUSTIFICATION OF THE RESEARCH PROGRAMME - 2

The many advantages of using an AGVS have already been noted, and in particular the need for an intelligent, flexible AGV able to operate in potentially noisy electrical environments has been demonstrated. There already exist many companies who supply AGVS which, to a greater or lesser extent, meet this requirement.

There are, however, two major disadvantages to these systems. The first is the present guidance system:

"Conventional methods for guiding vehicles automatically require the provision of rails, painted lines, beams of electromagnetic radiation, buried wires or other modifications to the environment which the vehicle is constrained to follow. In the case of systems based on rails or wires, a simple malfunction of a small part of the system may halt a large part of, if not all the system. White lines must remain unobscured to provide effective guidance. In nearly all existing systems for guiding vehicles automatically, vehicles cannot generally pass one another, and evasive action to cope with unexpected alterations to the guidance track (e.g. an obstacle on the rails) is generally impossible. At best the vehicle can only sense the obstacle and stop"[51].

Most applications use the wire guidance method where a simple break in the wire can halt a major part of the system, and 54% of users have suffered wire breaks[32]. Furthermore, the wire is expensive to install, requires the shut-down of the factory or warehouse during installation, cannot be altered by the user, and requires a major effort to change the route.

The working environment requires extensive modification; the guide wire must be laid and this means cutting up the floor - a costly operation[42]. Markers must be laid to inform the vehicles of loading points, junctions etc., and these are most often laid in the ground. This again is a costly and time consuming operation, and can even be dangerous; the tale is told of a first floor installation where so much extra weight was put into the floor that it collapsed!. An alternative to the magnetic guide wire is the white line system, and although this is much cheaper and simpler to install, it requires more maintenance to keep the white line clean and is easy to interfere with. Another AGVS tale concerns the shop floorman who looked up one day to see an AGV coming through the wall of his office, the white line having been tampered with!

The second major disadvantage is the equipment. A simple four truck installation can cost £350,000[42]. In most cases, the automated vehicle is sold complete with all its associated guidance equipment. This is fine for a new installation, but anyone wishing to automate an existing materials handling system is required to throw away any existing manual trucks he has. With trucks costing typically £12,000, this is no incentive to install an AGVS.

The Cableform research programme offers solutions to both of these problems. The development of a guidance system based on video information will free the vehicle of any need to keep to a particular path. Thus, there will be no problems with wire breaks; obstacles and other trucks can be manoeuvred around; installation and changes can be made by the user without the need to shut down the factory or warehouse; the absence of the need for environmental markers would alleviate the installation expense.

The independence of the control systems from the vehicles upon which they will be used is the hallmark of Cableform's corporate philosophy. Retro-fitting of the control systems is a natural consequence of the hardware transparency of the system. Although the new controller itself would possibly be more expensive than present controllers, it would certainly be more flexible and the savings on installation and the use of existing vehicles would more than compensate for this.

Furthermore, this concept, rather than placing a new product in an already highly competitive market, would open up a whole new market of customers who are looking for smaller scale projects with short term benefits.

The benefits which the proposed research programme will bring to Cableform have been listed in Chapter 1. On a broader scale, the following advantages can also be noted:

To the vehicle manufacturer: Hardware standardisation by the use of digital techniques will mean that a broad range of automated vehicles, from simple automatic guidance up to complete system automation, can be offered from just one basic vehicle design. This will increase the competitiveness of the vehicle manufacturer.

To the user: The use of an AGVS will enable the user to realise a more efficient materials handling system at a lower cost than his present system. Real time material tracking means improved stock control and can cut costs due to reduced levels of stock and work-in-progress. The ability to communicate between truck and Group Control at any time, irrespective of vehicle position, enables productivity to be increased and gives the system great flexibility.

To the national economy: The work will maintain a UK company as a world leader in the control of battery electric vehicles with consequent increased exporting opportunities, and the improved products will limit penetration of UK markets by foreign manufacturers.

3.6 SUMMARY

The aim of the research programme at Cableform Limited is to produce a free-ranging vehicle equiped with a highly flexible load handling system. The system must fit any vehicle and work in noisy electrical environments. The concepts of delegated intelligence and mathematical modelling will meet this specification. The use of delegated intelligence results in a functonal set-up of well defined system activities. The use of mathematical modelling enforces a modular design on the system components thus ensuring easy system expansion, and puts important system parameters in software, thus ensuring good system portability. The successful completion of the research programme would bring major benefits to Cableform, to the equipment manufacturers, to the end user and to the national economy.

CHAPTER 4

THE VEHICLE STEERING

4.1 Objectives

4.2 Present Steering Methods

    4.2.1 Physical Geometries

    4.2.2 Control Systems

4.3 The Steering Philosophy

4.4 The Operation of the Steering System

4.5 Summary

4.1 OBJECTIVES

Steering is the most autonomous of all the six vehicle sub-systems. It alone is able to operate independently of all the other processors and indeed one option that is commercially available is a bolt-on guidance unit for narrow aisle reach trucks which leaves the operator free for positioning his cab in the aisle at the correct location[19].

A review of present steering methods must include both the physical geometry of the steering system and the form of control system used since both of these affect the nature of the steering response. The steering philosophy developed from the system philosophy described earlier must obey the dictum of vehicle independence and include the advantages given by delegated intelligence and mathematical modelling.

Finally in this Chapter, the operation of the present form of the steering system will be described.

4.2 PRESENT STEERING METHODS

The methods of steering which are presently in operation in commercially available AGV's owe more to the technology of the early seventies than of the early eighties. The main reason for this is that it was in the sixties when most of the presently available systems were being developed and once a working steering system had been obtained, most of the advances have been in the performance of the complete AGVS and little or no attention has been paid to the steering system itself. Furthermore, all the steering systems developed have been for one particular steering geometry only, and there was no need to investigate the steering response in depth since the system could be designed experimentally by heuristic methods. This is even true of the bolt-on systems available since they are suitable only for narrow aisle reach trucks. As noted earlier these systems only work due to an unwitting feature of design[9] which allows feedback of some measure of the wheel angle. In reviewing these systems, two major elements may be identified; the geometry of the steering system and the form of the control system used.

4.2.1 Physical Geometries

Within the field of commercially available load handling vehicles, there are six categories of steering geometry. These are:

(a) Four wheels, steered from the front.

(b) Four wheels, steered from the rear.

(c) Three wheels, with a single steering wheel at the front.

(d) Three wheels, with a single steering wheel at the rear.

(e) Two transversely mounted wheels, driven differentially for steering, plus castors for stability.

(f) Two longitudinally mounted drive wheels, each individually pivoted, with castors for stability.

Physically categories (a) and (b) and categories (c) and (d) tend to have the same design and it is simply the direction of travel and the location of the guidance coils which distinguishes the different categories. Figures 4.1 to 4.4 show the geometry of the four basic designs with the positions of the coil assemblies marked on. In the cases where the steering axis is at the front of the vehicle, the coils nearest to the steering axis are used. When the steering axis is at the rear of the vehicle, the coils nearest to the fixed axis are used. Thus the coils are always at the front of the vehicle. It is worth noting that in cases (a) and (c) the coils are further ahead of the fixed axis than in cases (b) and (d). The distance between the fixed axis and the coils determines the phase margin of the system (see Section 7.4) and hence the system stability. It is for this reason that rear-steered AGV's always go slower than those which are steered from the front.

More frequently these days, commercially available AGV's are being offered with the option of bi-directional travel. This means that the vehicle is represented by two steering geometries; (a) and (b) if it is four wheeled, (c) and (d) if it is three wheeled. These vehicles always travel slower when steered from the rear than when steered from the front. This explains the popularity of the unit load transporter with steering geometry (e). The two drive wheels are in the centre of the vehicle, and due to the symmetry of the vehicle (see Figure 4.3) the vehicle is the same whether travelling forwards or backwards (however that may be defined for a symmetrical vehicle!). Thus it does not suffer from the reduced reverse speed problem and can operate with equal ease in either direction. As mentioned in Chapter 2, the faster the truck can operate, the more efficient the AGVS is. Thus in its environment the symmetrical unit load transporter has an important operational advantage.

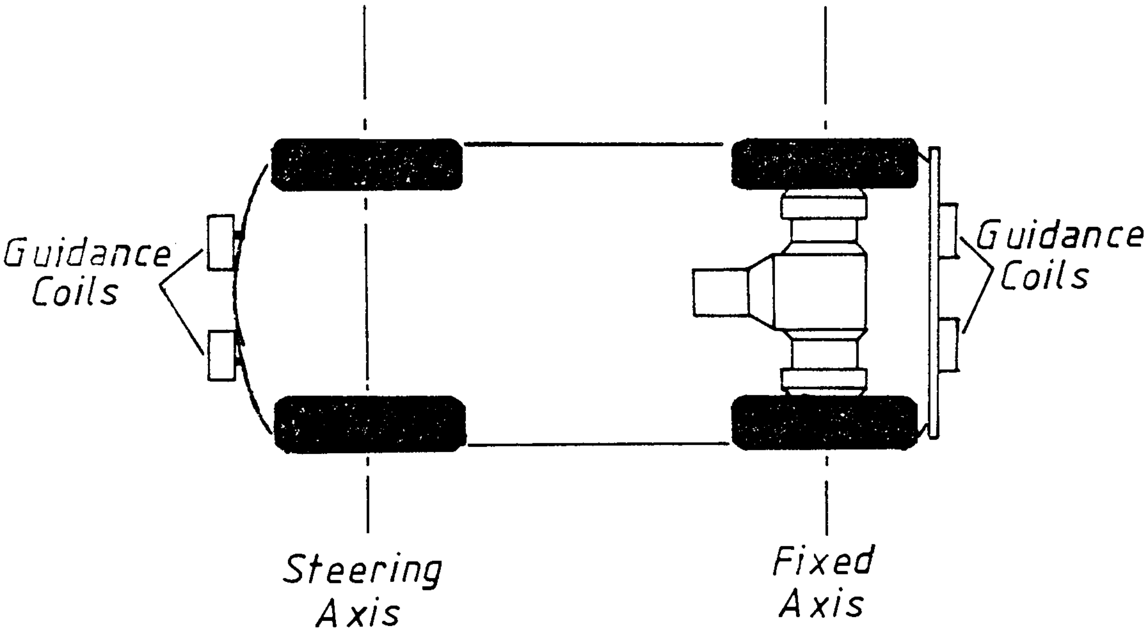


Figure 4.1- Steering Geometries A and B
-based on the Salev Fork Lift Truck range

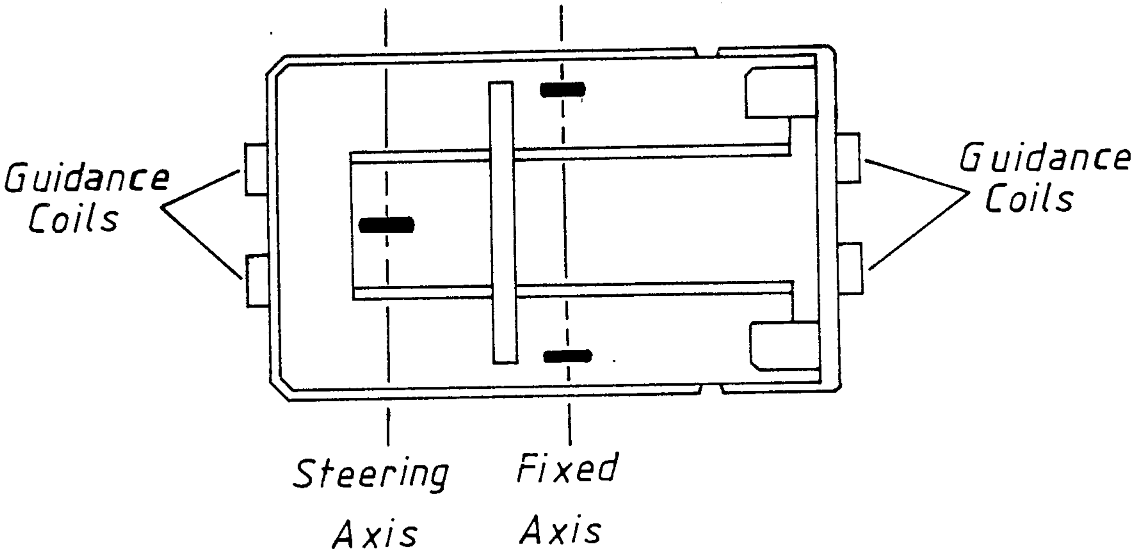


Figure 4.2- Steering Geometries CandD
-based on the ACS Assembly Carrier A-107

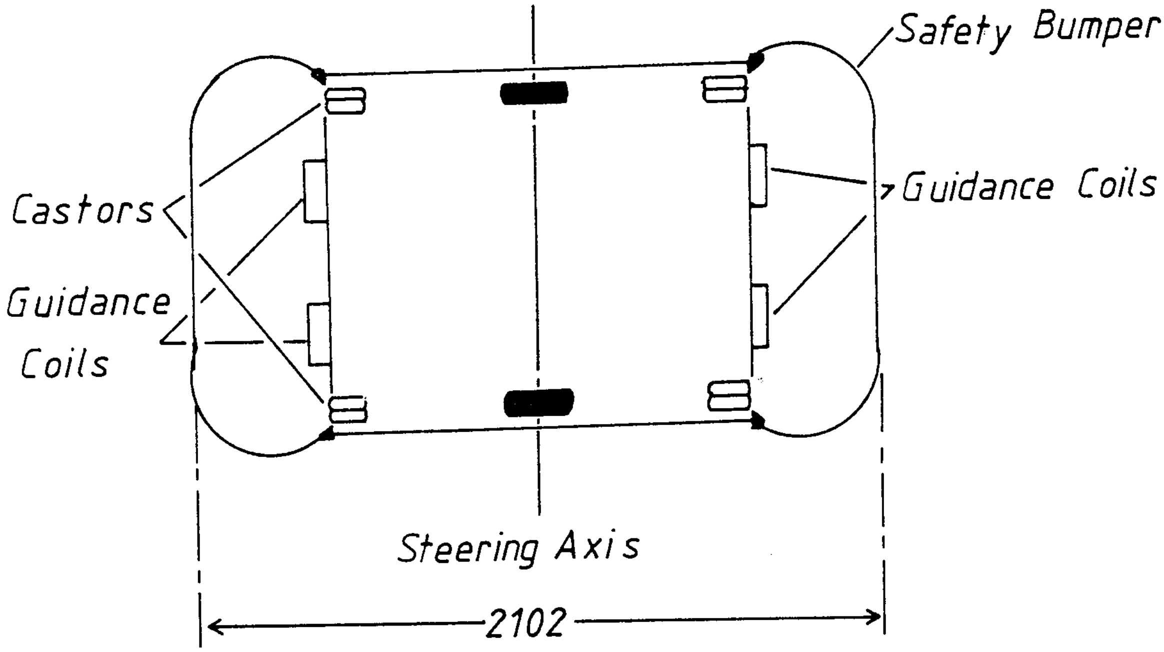


Figure 4.3 - Steering Geometry E

- based on the Digitron Robocarrier

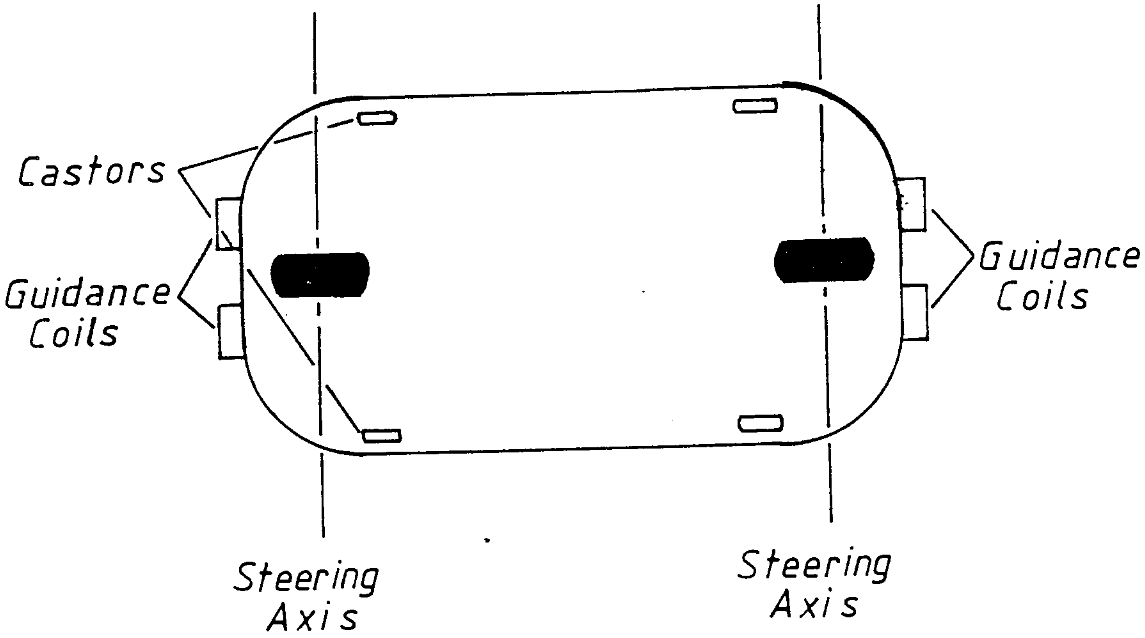


Figure 4.4 - Steering Geometry F

- based on the Seiv Automation Flexmatic

An important distinction can be made between categories (a) to (e) and category (f). Categories (a) to (d) have the steering axis, whether it is provided by two wheels or just a single wheel, either at the front or the rear of the vehicle. Thus there is only one steering axis. In category (e), where the differentially driven wheels are mounted on the same transverse axis, there is still only one steering axis, this time in the centre of the vehicle. However, in category (f), where the two drive wheels are mounted on a longitudinal axis and are individually pivoted, there are two steering axes. This means that by turning both wheels through 90 degrees, the vehicle can be made to travel sideways. This is not possible for a vehicle with only one steering axis. By allowing large steering angles to be placed on the steering wheels in categories (a) to (d), very tight radii of turn may be achieved and by driving the two wheels at the same speed but in opposite directions in category (e), the vehicle may be made to spin about its centre, but it can never move sideways. In practice, the difference between these tight radii of turn and the ability to go sideways does not give tremendously large space savings and if the vehicle is going into an existing materials handling operation which will already operate with single steering axis trucks, it becomes unimportant. Furthermore, the ability to move sideways introduces additional complexity into the control of the vehicle and must be met either by the provision of extra coils and control gear, or by some suitable form of dead reckoning algorithm.

The added complexity thus involved does not provide a corresponding increase in flexibility and so for an automatic vehicle, a geometry with a single steering axis is to be preferred.

Of the five single steering axis geometries, the ability of category (e) to spin about the vehicle centres gives it the tightest radii of turn. Categories (c) and (d) can spin about the back axle by setting a steering angle of 90^{o} on the steering wheel. Categories (a) and (b) can only usually set steering angles up to a maximum of about 30^{o} and so are the least manoeuvrable of all.

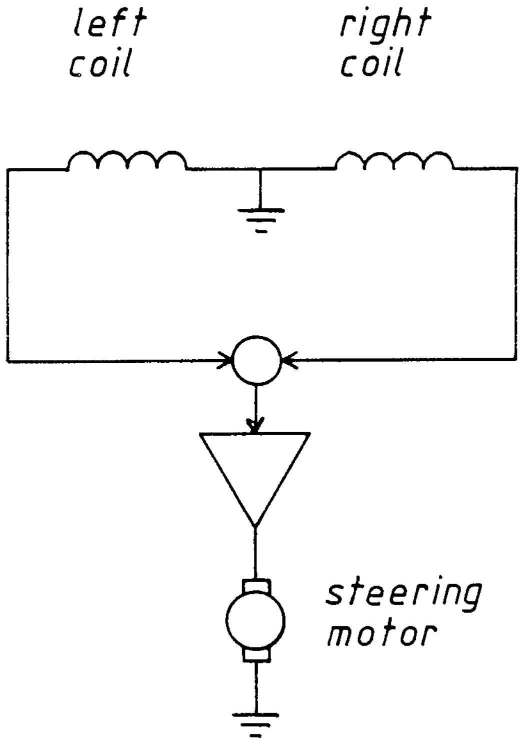
The six categories cover all the steering geometries used in industrial load handling equipment whether it be manually operated such as a hand pallet truck, powered such as a fork lift truck or completely automatic such as an AGV. Table 4.1 shows the main types of equipment together with the steering geometry involved.

4.2.2 Control Systems

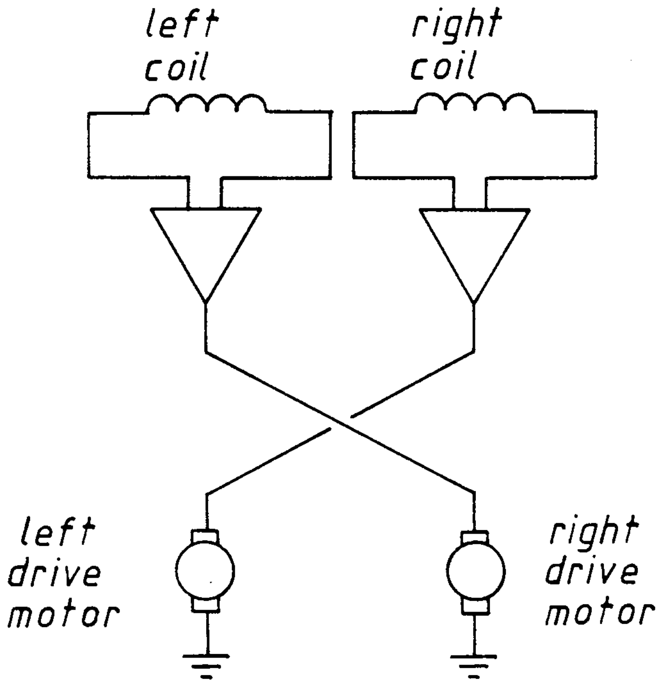
Within the field of commercially available AGV's there are two basic control schemes. In one scheme there is a single steering motor, separate from the drive motors, and so the signals from the two guiding coils have to be processed to produce a single difference signal. This difference signal must include both amplitude and sign information so that the vehicle can turn in both directions. In the other scheme, there are two drive motors which are driven differentially to provide steering. In this case the coil voltages can, upon amplification, be applied directly to the motors. The two different schemes are shown in Figure 4.5 and will now be discussed in more detail.

TYPE OF EQUIPMENT	STEERING GEOMETRY
Towtractors and Trailers	A, C
Fork Lift Trucks	B, D
Side Loaders	A
Straddle Trucks	A
Platform Trucks	A
Unit Load Transporters	C, E, F
Narrow Aisle Stackers	C, D
Reach Trucks	C, D
Order Picking Trucks	C, D
Pedestrian Controlled Stackers	D
Stillage Trucks	A
Hand Pallet Trucks	C, D

TABLE 4.1: MOBILE MATERIALS HANDLING EQUIPMENT



a) single steering motor



b) differential drive motors

Figure 4.5 - Steering Control Schemes

(a) Single Steering Motor

When using a single steering motor, steering information which includes amplitude and sign must be generated. Figure 7.6 shows the amplitude distribution of the alternating voltage generated in a single coil near to a long straight wire carrying an alternating current. The use of two coils where the voltage in one coil is subtracted from the voltage in the other allows the generation of a difference signal as shown in Figure 2.2. Commercially to achieve this difference signal, the output of two coils, one of which is wound in opposition to the other, are simply added. The phase of this composite signal must now be compared to a reference signal to provide the sign data, i.e. whether to turn the wheels to the right or to the left. Thus this method requires the provision of an extra set of coils to provide a reference signal against which to compare the phase of the difference signal. The requirement for the extra set of coils can be by-passed if the amplitudes of the signals in the individual coils are recovered. A simple subtraction of one from the other then yields the necessary amplitude and sign information. In practice this may mean the use of an extra amplifier in the control electronics and in the early days of AGV's this was worth avoiding by supplying two extra coils. However, with the decreasing cost and increasing complexity of solid-state electronics, operational amplifiers are now both cheap and easy to use and it is far preferable, both from an engineering and a financial point of view, to use just two coils and somewhat more sophisticated control circuitry.

(b) Differential Drive Motors

When both steering and traction are supplied by the same motors, the signals from the two coils are applied individually to the motors. Firstly, with the vehicle in the correct position on the guide wire, the amplitudes of the two signals are recovered and then put through an amplifier to provide the motors with their drive at the set speed of the vehicle. Each coil supplies just one of the two drive motors. Then any change in the amplitude of the coil signal will affect the power to the motor and hence steer the vehicle. For the system to be a negative feedback system, an increase in coil voltage on one side of the vehicle must inversely affect the speed of the motor on that same side of the vehicle with respect to the speed of the other motor, i.e. if the left-hand coil comes closer to the wire than the right-hand coil, then the vehicle must turn to the left and this is achieved by making the left side drive motor run slower than the right side motor. This can be done either by cross-strapping the coils and the motors so that the left-hand coil drives the right side motor and the right-hand coil drives the left side motor, or by connecting the coil to the motor on the same side and inverting the effect of a change in coil voltage relative to its quiescent value, such that an increase in coil voltage slows the motor down and a decrease in coil voltage speeds the motor up.

These are the two basic control schemes for the automatic control of vehicle steering. As found in industry, the methods are based on analogue techniques and both schemes, at some time or another, involve the handling of d.c. voltages. This unfortunately makes the steering systems sensitive to variations in component values due to tolerance values and the general ageing of components. Thus part of the general system maintenance must involve the checking and "re-tweaking" of the steering control system.

Furthermore, these analogue systems have all been specifically developed for the vehicles upon which they are used. Thus, although they work generally well, the system portability is not good and in cases where the system is used on another vehicle, system stability is not guaranteed. Thus AGVS suppliers tend to offer a range of vehicles with the steering system indivdually tailored to the particular vehicle chassis. Although such a policy is effective and reliable, it does mean that the end user cannot use his existing fleet of load handling vehicles in an automatic operation, and the automation of a new design of vehicle entails the development of a new steering system.

4.3 THE STEERING PHILOSOPHY

The system philosophy, as outlined in the previous Chapter dictates the need for vehicle independence, system noise immunity and ease of up-grading as the prime requirements for the AGV's. It further stipulates that this will be achieved through the use of delegated intelligence and digital techniques coupled with mathematical modelling. The aim of the development programme, as it refers to lateral position control, is to develop a system which can provide real-time guidance information from a T.V. picture (see

Section 3.2). Initially, however, the guidance information comes from a magnetic sensor in the form of a guide wire and two vehicle mounted coils. The steering philosophy must ensure the compatibility of these two different sensors and the other sensors which will span the development gap between them. The steering philosophy is based on three concepts:

(a) Modular structure.
(b) Mathematical modelling.
(c) Software resident parameters.

How these concepts provide the steering philosophy will now be considered:

(a) Modular Structure

Figure 4.6 shows a block diagram representation of the steering system of an AGV. The reference input, REF, determines the track that the vehicle is required to follow. It is compared with the vehicle lateral position signal, SIG, as supplied by the lateral position sensor and any difference between the two forms a steering demand. This is a demand for a specific steering angle and is used as the input to the inner loop which is a closed loop angle demand system. The angle demand is compared with the actual wheel angle input as supplied by the wheel angle sensor and any difference between the two forms a system error ERW. This error is then amplified and applied, through suitable circuitry, to the motor. Four main functional units may be identified and these are:

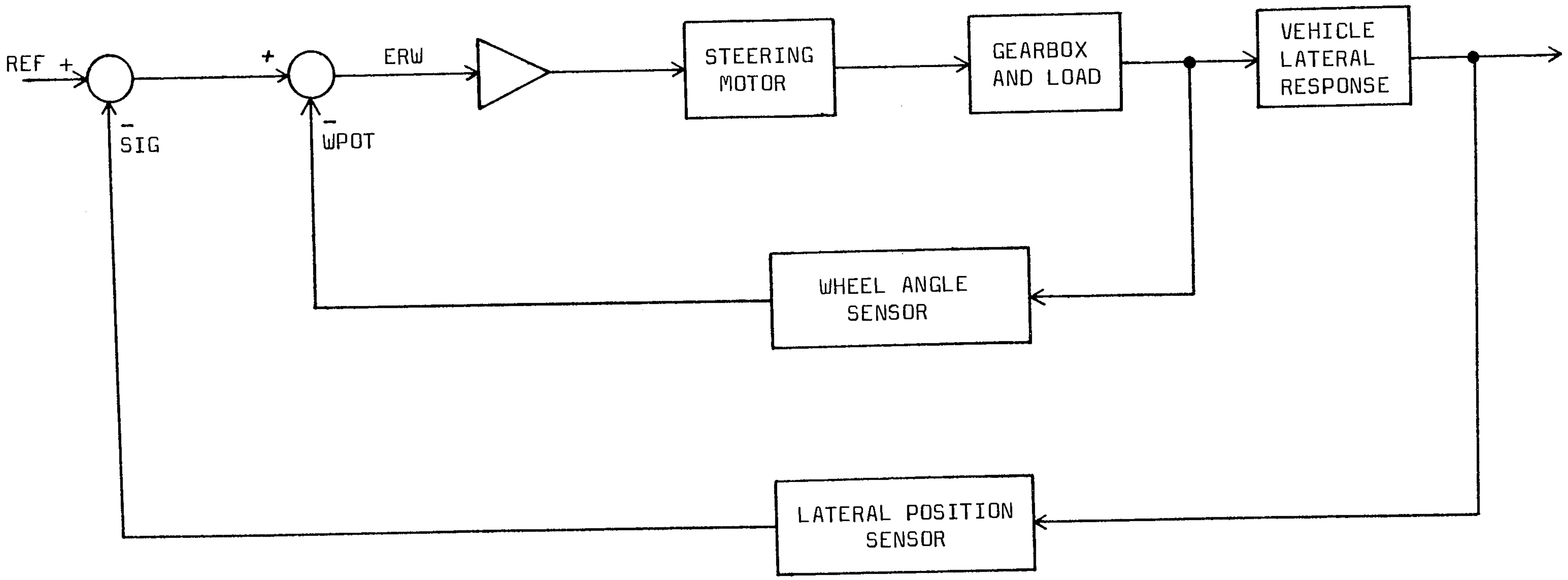


FIGURE 4.6 – BLOCK DIAGRAM OF THE A.G.V. STEERING SYSTEM

(a) The steering motor and gearbox.

(b) The vehicle.

(c) The wheel angle sensor.

(d) The lateral position sensor.

Within a stable closed loop system, the input and output profiles of all four of these units can be defined. For example for a separately excited, armature controlled d.c. motor, the d.c. gain value is approximately 1/Bm (see Section 5.2), where Bm is the motor constant. Thus the input/ouput profile of the motor looks like Figure 4.7 and any motor which can supply the same profile can be interchanged without affecting the system performance. The lateral position sensor profile is given in Figure 4.8. Any deviation of the vehicle from the required track generates a signal which if it differs from the reference value will cause an angle to be put on the steering, and hence turn the vehicle back to the required track. Referring to Figure 2.2 it can be seen that the magnetic sensor difference signal provides this form of profile, except with an electrical output, as long as the lateral displacement does not exceed the value at which the response starts to go non-linear. Any lateral position sensor which can generate this profile can be interchanged with the magnetic sensor with no effect on the system performance. As new sensors are developed they can be substituted on the vehicle and guide the vehicle with no operational difference. Thus as mentioned in Section 3.2 the basic design of the steering system will not change, but rather the vehicle will be able to perform the guidance function with less need to alter the environment and with a greater range of

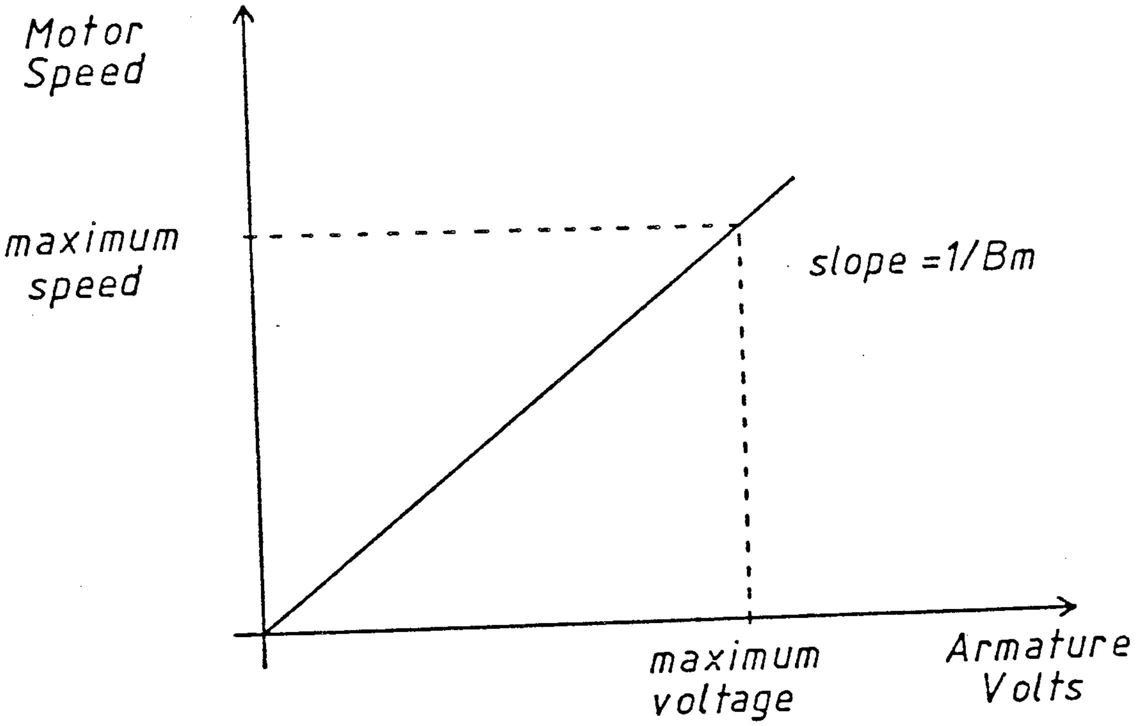


Figure 4.7 - Input-Output Profile
D.C. Separately Excited Motor

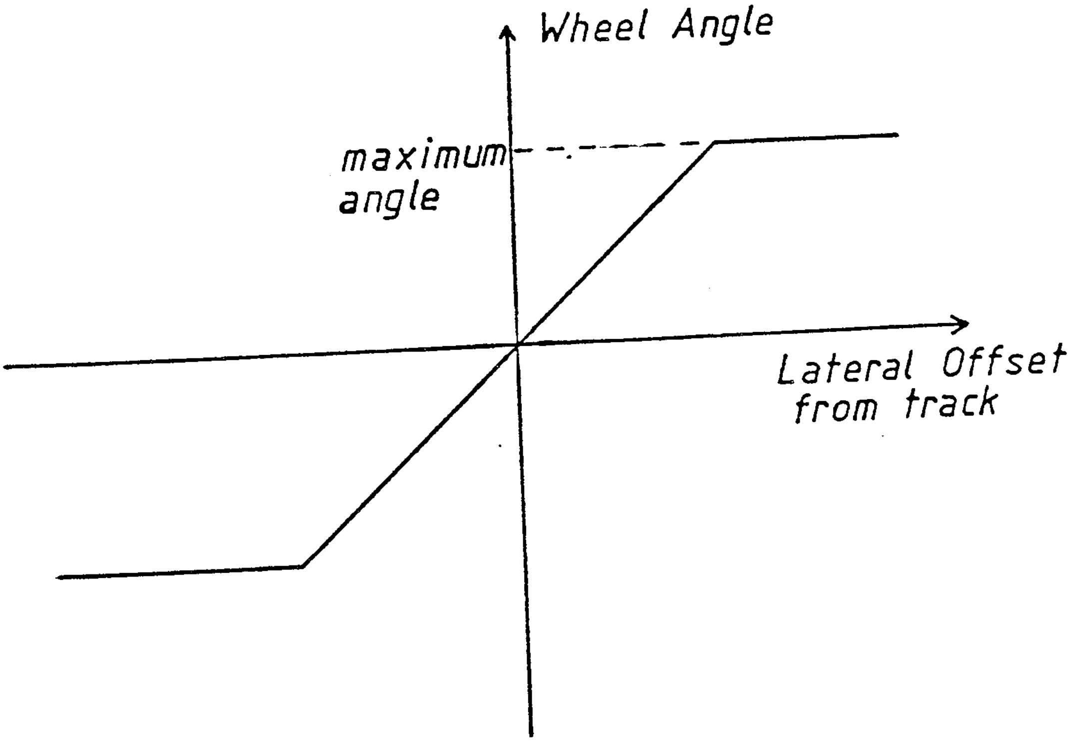


Figure 4.8 - Input-Output Profile
The Lateral Position Sensor

possible operations. Thus the modularity of the design ensures the ease of up-grading the system. The advantages of modularity, however, are not confined to the lateral position sensor. Any of the five functional units can be replaced, so that a new steering motor may be fitted for example, or the system could be used on a different vehicle. Indeed, any part of the system may be replaced providing the profile it presents at its modular interface is maintained. Practically, however, if the same wheel angle to lateral displacement profile is to be maintained, then only a vehicle exactly like the previous one may be used. If a different vehicle is used which in some way alters this profile then if the system is to show vehicle independence it must in some way compensate for this. To consider how this is done it is necessary to look at the concepts of mathematical modelling and software held parameters.

(b) Mathematical Modelling

The use of modularity in the steering system design allows the interchangeability of units with the same input/ouput profile. When, however, the new unit differs in some way, for example, a vehicle with a longer wheelbase, then the effect of this difference must be compensated for. In order to compensate for any differences in the new unit, the effect of these differences must first of all be determined. One way in which to do this would be to test each new unit thoroughly, doing a complete set of frequency and step response tests on each new unit. While certainly accurate, this method is very long-winded and in requiring skilled men to test each new vehicle, is also rather expensive.

The alternative method is to develop a mathematical model of the system. The use of a mathematical model allows the identification of those parameters which affect the performance of the system. For example, it will be shown in Section 5.3 that the important vehicle parameters in the steering system are the wheelbase, the sensor position, the speed of the vehicle and the steering angle. The vehicle speed and the wheel angle are dynamic quantities and so must be measured or preset, but the wheelbase and the sensor position are static quantities and their values can be pre-set into the control loop. The mathematical model shows the effect of these parameters on the system performance. This is known as the sensitivity of the parameter[46] and knowledge of the parameter sensitivity allows alteration of system variables, principally the gain, to ensure stable system operation.

(c) Software Resident Parameters

The use of a mathematical model allows the identification not only of the important system parameters, but also of the effect that those parameters have on the operation of the system. Knowing this, alterations can be made to the system to ensure stable operation. Traditionally, this would be done by means of variable resistors or select-on-test resistors. The disadvantage with this system is that variations in resistor values would affect system performance. Low tolerance resistors would be needed and these are very expensive, particularly variable ones whose stability is generally poor anyway. Furthermore, the change in resistor value with ageing would mean that constant maintenance of the steering system would be required. The alternative is to use the software of the steering microprocessor. This is of course not an option open to most systems since they are analogue based, but by holding the value of such system variables as are affected by parameter changes in software, the mathematical model can be used to generate the value of these variables and then they can easily be changed in software. This merely involves the changing of a few lines of source code and then the programming of a PROM. There are no tolerance problems with software and the accuracy and resolution of the variable is set solely by the resolution of the microprocessor. Furthermore, there are no ageing problems. But it is not only static quantities that can be held in software. By using a database, dynamic quantities can also be kept in software. Thus data about the steering system which is operationally important, such as the level of the signal in the two coils and the wheel angle, can be put into the database and is then available for use in various system routines. For example, the signal level in the two coils, besides being used to generate the difference signal, is also used to check that there is a signal in the wire. Thus if both signal levels are below the noise level, the steering processor immediately generates a loss of guidance message. Nor need the data be confined to the steering processor. If the data are put in that area of the database which is communicated to Vehicle Executive then it can be made available to all the processors on the vehicle. Thus in a future application where the vehicle movement is calculated by counting the wheel revolutions, a patch of oil could cause problems by making the wheel on one side slip and give an artificially high count on that side.

This would be interpreted as a turn on the part of the vehicle and from the two wheel counts the radius of turn and hence the steering angle could be calculated. However, the error can be avoided if this angle is then compared with the value in the steering routine and not only is the oil patch problem avoided, but the vehicle could warn Group Control of the existence of the oil patch in the working area.

Thus the use of a mathematical model identifies the effect of parameter changes on the system, and by altering software based parameters a stable system can be achieved without the need to individually test each new vehicle and without the tolerance, ageing and maintenance problems of traditional analogue based steering systems. Hence the system design can be made independent of the vehicle to which it will be fitted and a perfect match between vehicle and controller is made by a few lines of software. The use of a database allows important system variables to be held in software, to the benefit of all the vehicle system processors and permits the use of a software philosophy based on the modularity concept. Of course these advantages also apply to other units in the system so that if for example a new steering motor were put in with a different armature volts to shaft speed profile to provide better performance or because it was cheaper, then this too could be catered for.

This description of the steering philosophy is independent of the form of the control systems used to implement it. Thus, it is defined for all six projects throughout the whole research programme.

4.4 THE OPERATION OF THE STEERING SYSTEM

This Section gives a description of the operation of the wire guidance based steering system of project one. It is based upon the software control of a closed loop angle demand system, whose input is derived from a lateral position sensor. Figure 4.9 shows the steering system control circuitry. The microprocessor reads in information from its external sensors through an analgoue-to-digital converter or ADC. The sensors consist of: the lateral position sensor which measures the lateral deviation and provides the input to the closed loop angle demand system or inner loop; the wheel angle sensor which provides the feedback for the inner loop; and the manual controller or manual box, which gives traction and steering data to the system when the manual option is selected.

The ADC is controlled from the microprocessor through a parallel input/output (PIO) controller. This is the control PIO shown in Figure 4.9. It sends signals to the ADC to determine which sensor the ADC is to look at, and to start the ADC converting. It also receives the signal from the ADC which informs the microprocessor that the ADC has completed the conversion of the analogue signal. This is the end-of-conversion or EOC signal. The control PIO is also responsible for the receipt or transmission of the system control signals. These comprise: a digital word which sets the width of the pulse in the pulse width modulated (PWM) signal which is sent to the motor; the direction or DIR signal which is used to control the direction of the motor; the input signal from the manual box which requests manual operation; and an output line to the re-triggerable monostable.

The digital word is sent to a counter timer chip (CTC) which produces the PWM signal according to the word sent to it. The PWM and DIR signals are then sent via the Motor Driver Circuit to the motor. The input signal from the manual box causes the microprocessor to read in the steering and traction data from the manual controller and to use that to control the vehicle in place of the sensor data used when in automatic control. The monostable is connected to a direct current contactor in the traction motor circuit as mentioned in Section 3.2 and stops the vehicle in the case of a failure of the steering processor or a communications failure between Vehicle Executive and the steering processor.

The monostable and the CTC along with other components necessary for the production of the PWM signal and the interface between the motor driver circuit and the microprocessor, are included with the ADC and the control PIO on a single integrated interface board. This is shown in Figure 4.10. The bi-directional communications with Vehicle Executive is controlled through a dedicated PIO. This is the communications PIO which is on the same board as the microprocessor and can be seen in Figure 4.9.

The inner loop of the control system is shown in Figure 4.11. The loop input is the steering angle demand which is the difference between the input signal SIG and the reference REF.

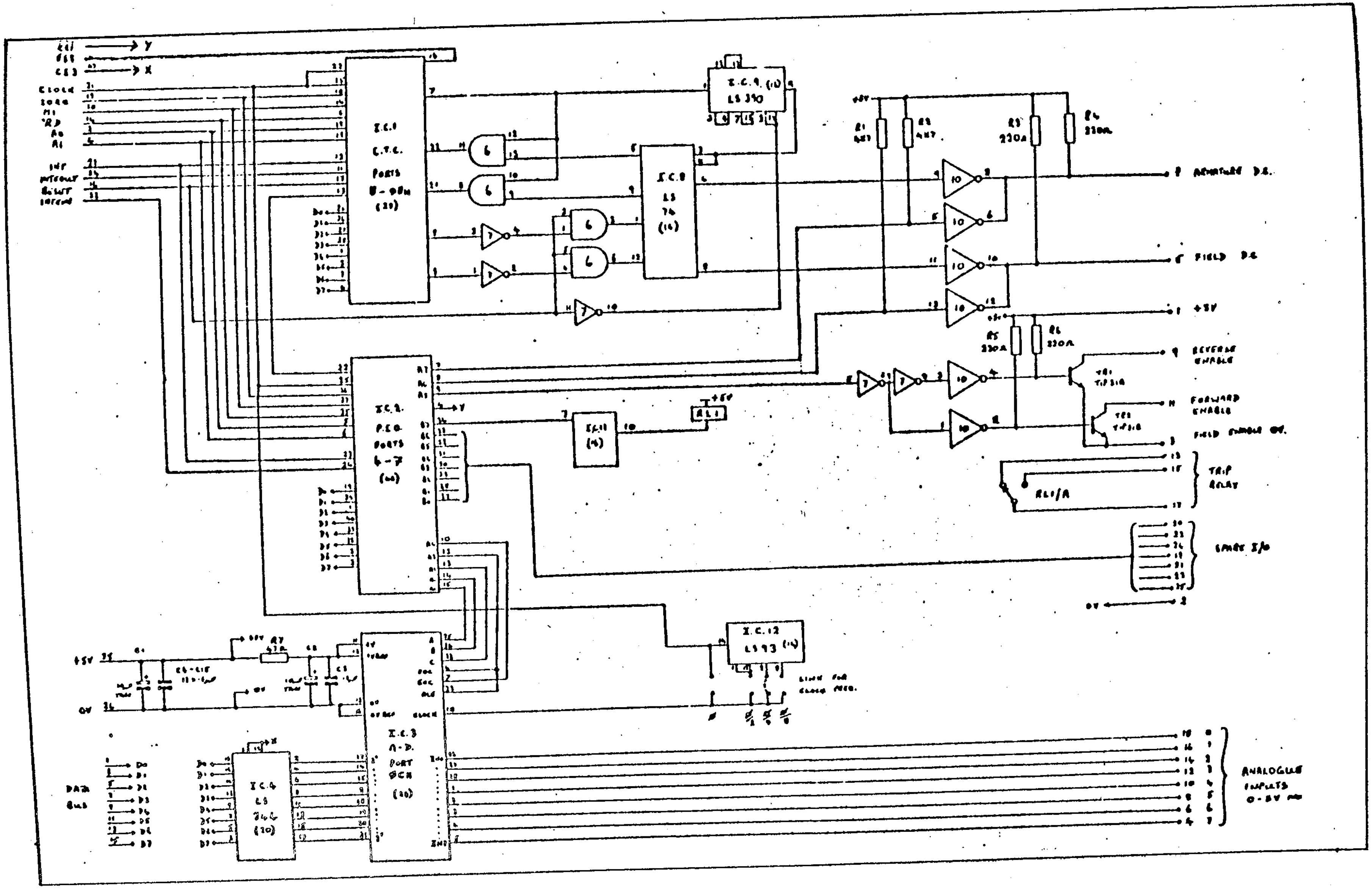


Figure 4.10 The Integrated Interface Board

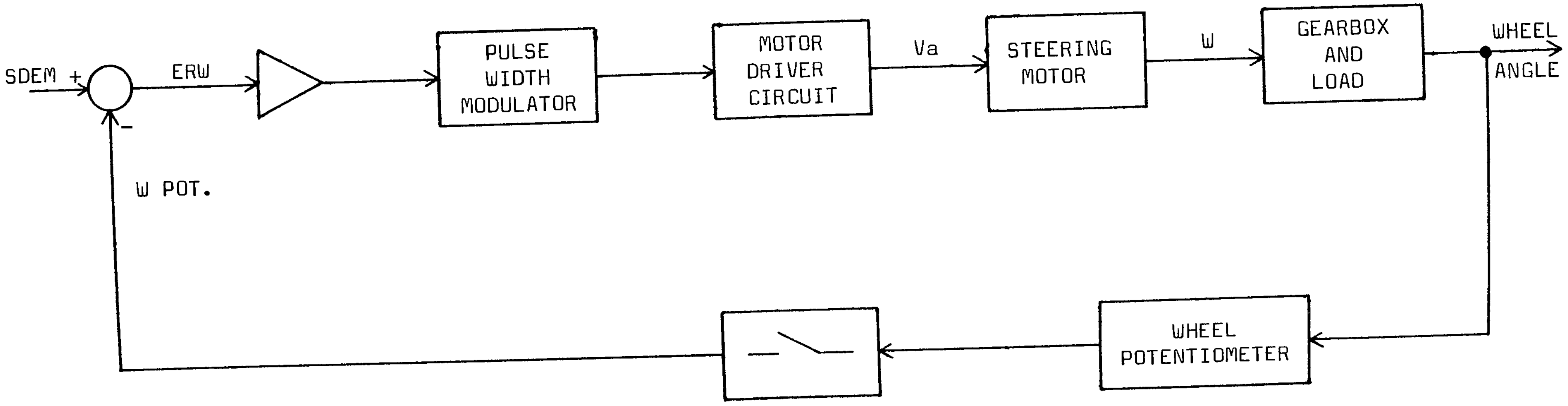


FIGURE 4.11 – THE CLOSED LOOP WHEEL ANGLE DEMAND SYSTEM

The position of the wheels is sensed by a potentiometer which is attached to the output shaft of the gearbox and it is the potentiometer voltage after being turned into a digital signal WPOT by the ADC, which is compared with the steering demand to provide the system error, the digital word ERW. This error signal is amplified in software, taking care to avoid signal wrap-around, and then sent out to the CTC on the interface board. The CTC is set every 2.3 milliseconds to give a five volt level on its output and the digital word sent to it determines how long its output stays high before being brought low to zero volts. Thus the output of the CTC is a train of pulses of fixed frequency (750 Hz) whose on-time is determined by the digital word sent to the CTC, and it behaves as a pulse width modulator. The PWM signal is fed into the motor driver circuit which interfaces between the PWM and the motor. As the motor turns, its geared down output turns the wheels in such a way as to reduce the difference between the steering demand and WPOT. The use of this closed loop system in the heart of the steering system means that wheel angle feedback has been deliberately engineered into the system and is not an unwitting feature of design. Figure 4.12 shows the three sources of the digital word SIG. In the automatic mode, the voltages from the two coils are digitised directly and read into software. There the signals are full wave rectified and the average value of 32 samples of each coil is taken thus providing a measure of the signal amplitude. These average values are the digital numbers RS and LS which represent the right side and the left side coils respectively. Their difference forms the digital number SIG. The form of SIG is a twos complement number wherein the most significant bit gives the sign of the number and all the other bits give its value. The sign bit is used to denote direction; a one meaning a

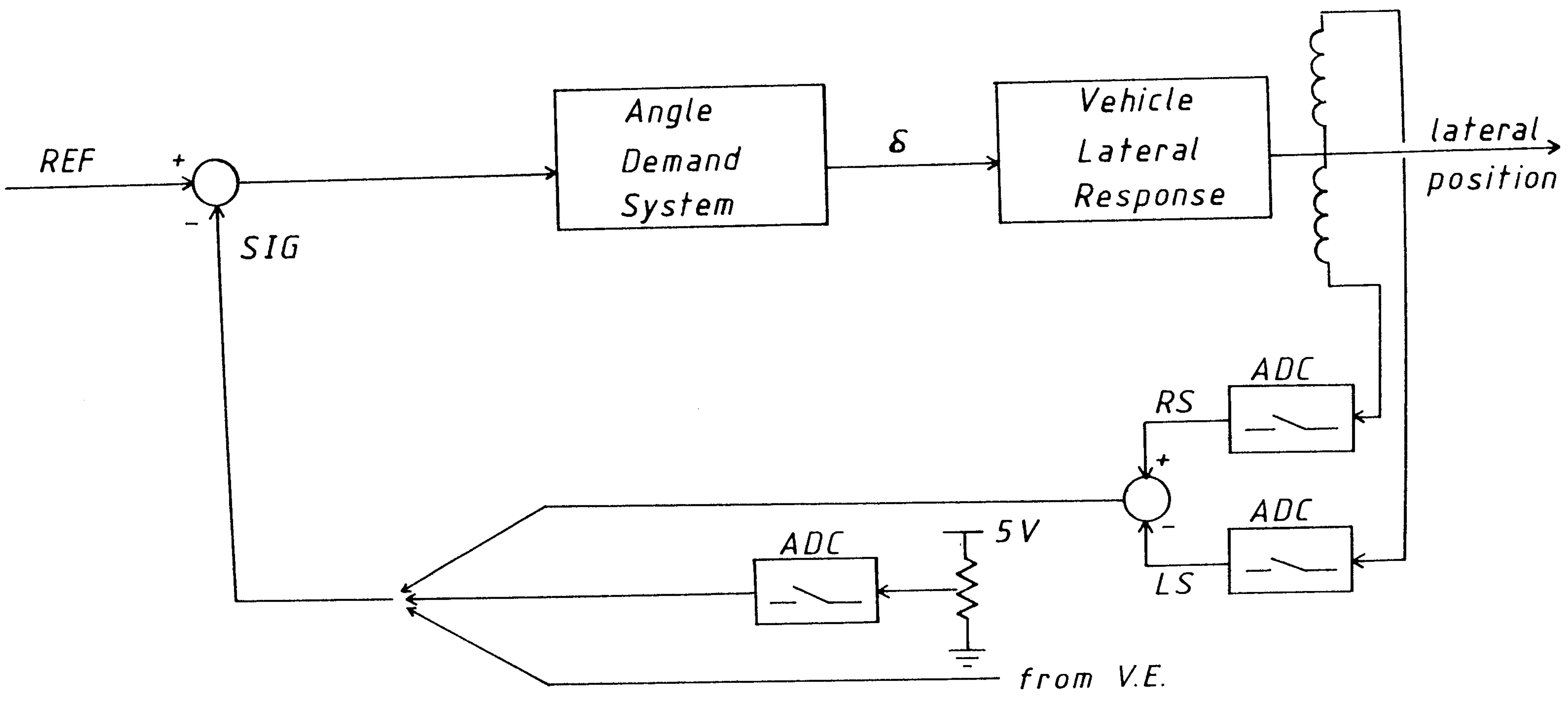


Figure 4.12 - The Three Sources of the Digital Word SIG

turn to the left and a zero meaning a turn to the right. In the manual mode, the digitised voltage of a hand held potentiometer is read in and a number equivalent to its quiescent d.c. level is subtracted from it to provide a twos complement value of SIG. During software controlled manoeuvres the digital value of SIG is provided directly by Vehicle Executive in twos complement form. By whichever method provided, SIG is then compared with the digital reference value REF to form the steering demand.

The use of a database means that no special arrangements are necessary to allow Vehicle Executive to demand a software controlled manoeuvre. It simply places the value of the angle it wants in the database location of SIG and the programmme will execute as usual only with the Vehicle Executive value of SIG instead of its own calculated value. In order to do this the Vehicle Executive has to have some way of letting the steering processor know that it wishes to do so. This it does by means of a flag. This flag is a single bit within a register which if it is set tells the steering software to ignore its own value of SIG and use the one provided by the Vehicle Executive. If the flag is not set, programme operation continues as usual. The flag used for this purpose is the most significant bit of the first byte of the information sent over by Vehicle Executive. This use of flags to signify system status and hence effect programme operation is used more generally. If the steering processor detects a loss of guidance signal it sets the wire lost flag then requests communications with Vehicle Executive. The least significant bit of the first byte of the information it sends to Vehicle Executive is the flag whose condition tells Vehicle Executive about the state of the guidance signal. A one indicates that there is a signal in the wire and a zero indicates that there is no signal there. Similarly, the least significant bit of the second byte is used to indicate whether the steering is in manual or automatic control. A one indicates that the steering is under manual control while a zero means that it is under automatic control.

These are examples of status flags whose information is of interest to external processors as well as the steering processor. Some status flags are of internal interest only and in the steering system these are the direction flag and the data valid flag. The direction flag determines the direction in which the vehicle is to be steered; a one corresponding to steer left and a zero corresponding to steer right. The data valid flag is used to prevent data from one sample interval being mixed up with data from another sample interval. The flag is initially reset to zero and it is only set after a complete batch of data has been read in. The main programme cannot pass into the section which accesses the database until the data valid flag is set. Once the data valid flag is set, the programme moves on into that section and immediately resets the data valid flag so that the database cannot be accessed a second time until a second batch of data has been read in. In this manner only coherent sets of data can be accessed.

Thus the closed loop angle demand system may be operated on by a signal from one of three sources. Since the angle demand control system is software controlled, its input must be a digital signal. Flags are used to monitor the system status and so affect system behaviour.

4.5 SUMMARY

Within the field of commercially available mobile load handling equipment, vehicles with a single steering axis are to be preferred for automatic operation and those which can travel at high speed, bi-directionally, show an important operating advantage. Present systems are somewhat dated and have the disadvantage of being custom-built for that vehicle, that steering motor and that speed. A more modern system based on a mathematical model and built according to the concepts of modularity and software residence of important system parameters has many advantages. System stability is designed in with the inclusion of wheel angle feedback and system portability is good due to the simplicity and accuracy of the software held parameters. The modularity of the system ensures that the system is easy to upgrade from a hardware point of view and the software modularity made possible by the use of a database means that the software can be easily upgraded too. The use of a database gives easy access to important system variables which describe the state of the system and flags are used to indicate the present state of the system.

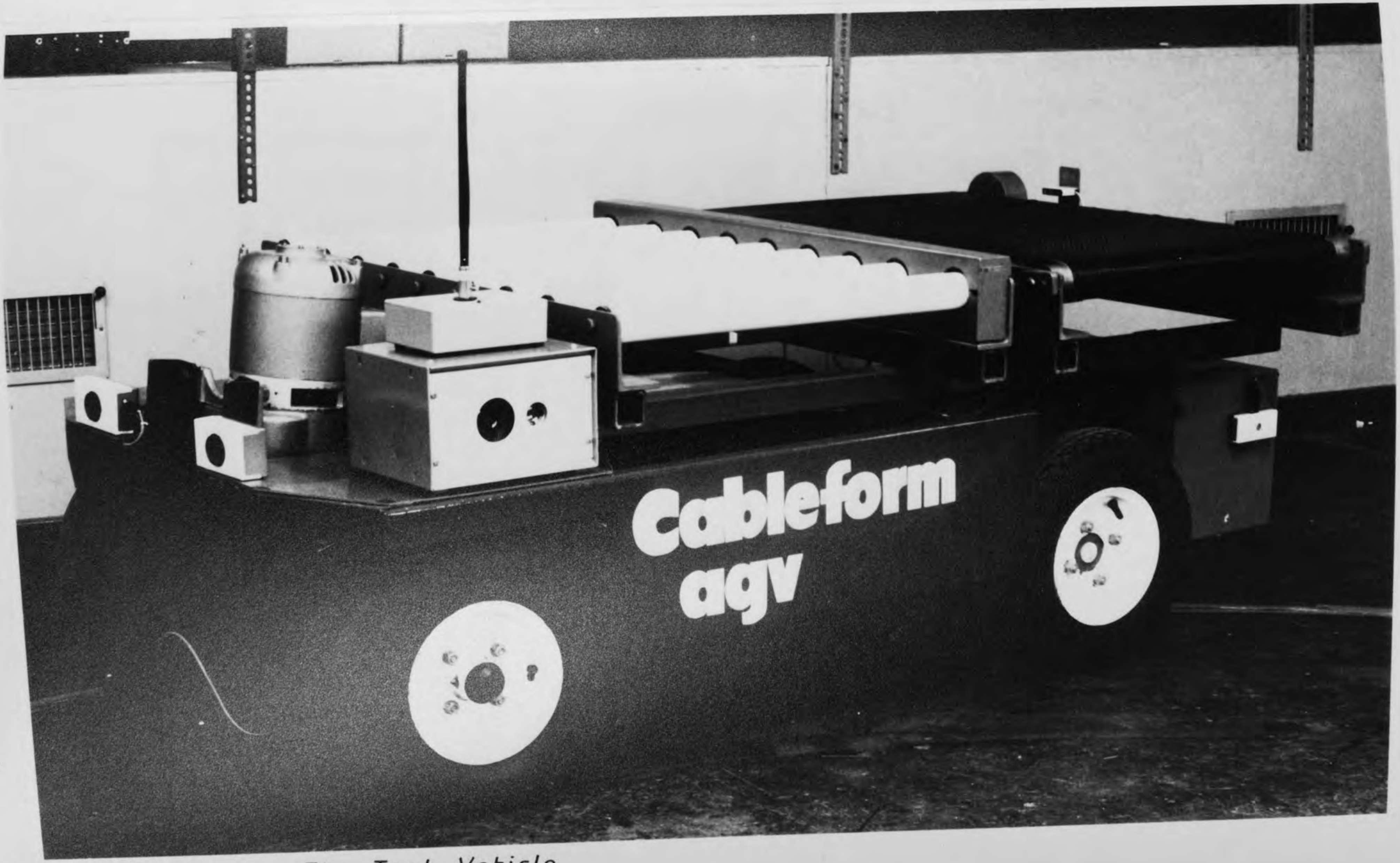


Plate 1 - The Test Vehicle

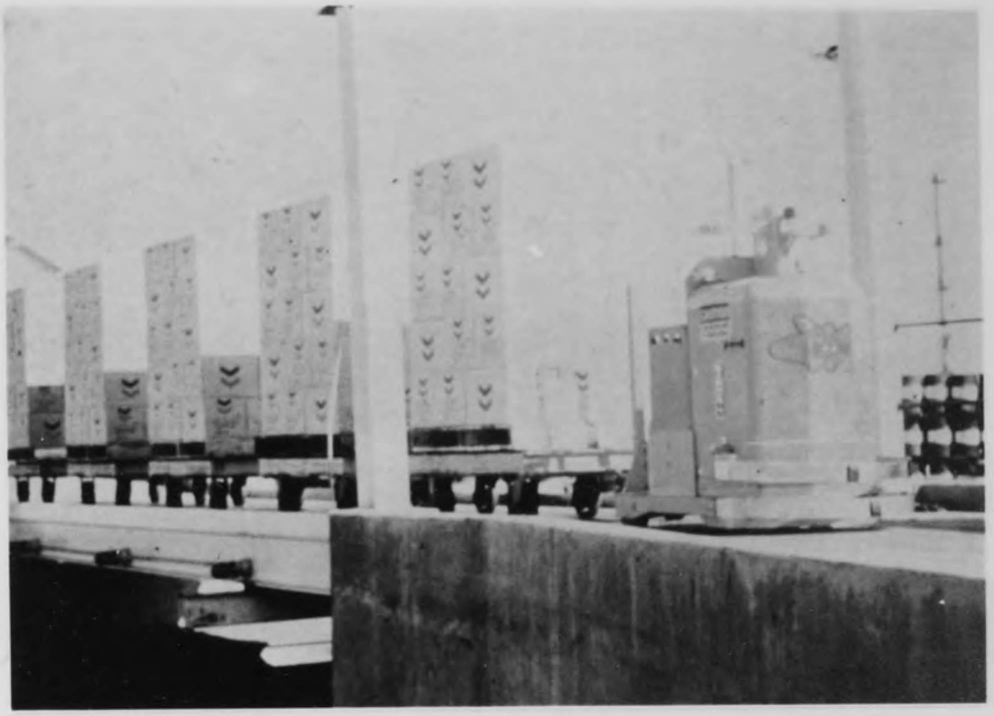


Plate 2 - Towtractor with Trailers

Plate 3 - Automatic Fork Lift Truck

Plate 4 - Pallet Platform Type Vehicle - 1

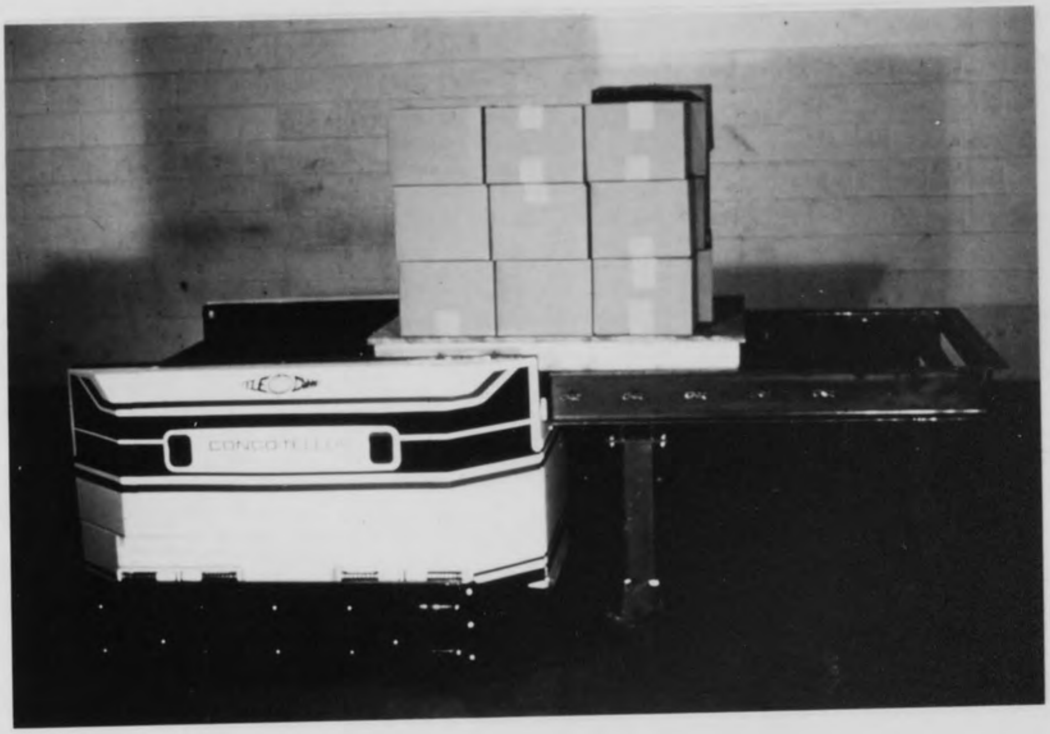


Plate 5 - Pallet Platform Type Vehicle - 2

CHAPTER 5

THEORETICAL ANALYSIS OF THE SYSTEM RESPONSE

Plate 2 - Towtractor with Trailers

Plate 3 - Automatic Fork Lift Truck

Plate 4 - Pallet Platform Type Vehicle - 1

Plate 5 - Pallet Platform Type Vehicle - 2

5.1 OBJECTIVES

There are two basic components in the model of the steering system of an automatic vehicle. One is the control system used to turn the wheels which relates the angle placed on the steering wheels to the input signal of that system. The other is the response of a vehicle to an angle set on its steering wheels. The mathematics developed for the control system will be for a separately excited, armature controlled, d.c. motor, since this is the type of control system used, but the form of the model developed from the mathematics will allow the use of any control system which for an input signal places an angle on the steering wheels (see Appendix D). The mathematics developed for the vehicle response will be for a four wheeled vehicle with a single steering axis, since this is the type of vehicle which was controlled, but the form of the model will allow use of any vehicle response scheme. In actual fact, the vehicle response model developed is suitable for any single steering axis vehicle and so covers the majority of industrial battery electric vehicles. The mathematics of the lateral position sensor is then developed. This is not used in vehicle simulation since the sensor may be represented by a simple gain factor, but allowed the characteristics of the sensor to be investigated and the sensor design optimised. The mathematics is followed by the development of the vehicle model based on these mathematics.

5.2 STEERING MOTOR, GEARBOX AND LOAD - THE THEORY

5.2.1 Armature Volts to Motor Speed

Figure 5.1 shows a separately excited, armature controlled, d.c. motor.

For a constant value of field current the rotating machine equations become[46,47]

$$T = Bm \; Ia \tag{5.1}$$

and

$$Vg = Bm \; w \tag{5.2}$$

where T is the torque generated by the motor

Bm is the motor constant

Ia is the current in the armature

Vg is the back emf generated in the armature

and w is the armature shaft angular velocity

Applying Kirchhoff's voltage law to the armature circuit

$$Va - Ia\,Ra - s\,Ia\,La - Vg = 0 \tag{5.3}$$

where Va is the voltage applied to the armature

Ra is the armature resistance

La is the armature inductance

and s is the Laplace operator

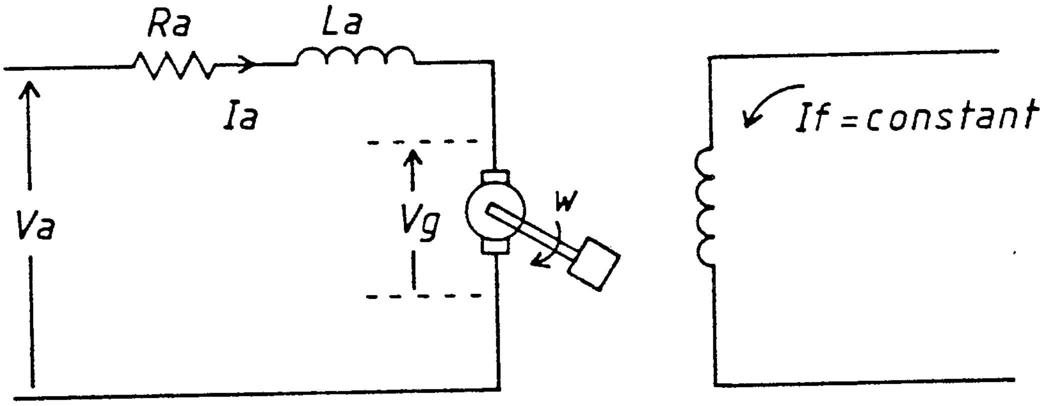


Figure 5.1 - The Separately Excited Armature Controlled D.C. Motor

Thus

$$Ia = \frac{Va - Vg}{Ra + sLa} = \frac{Va - Bm\ w}{Ra\ (1 + sTa)} \qquad (5.4)$$

where $Ta = La / Ra$ is the armature time constant.

The torque balance equation on the output shaft is given by

$$T = J\,\alpha + Bv\ .\ w + Tq \qquad (5.5)$$ [46,47]

where J is the armature shaft moment of inertia

α is the armature shaft angular acceleration

Bv is the coefficient of viscous friction for the armature

and Tq are the torque losses

Noting that $\alpha = sw$ gives

$$\begin{aligned} T &= w\ (Bv + sJ) + Tq \\ &= w\ Bv\ (1 + s\,T_L) + Tq \qquad (5.6) \end{aligned}$$

where $T_L = J/Bv$ is the mechanical time constant.

Substituting in equation 5.1 for T from equation 5.6 and Ia from equation 5.4 gives

$$w\ Bv\ (1 + s\,T_L) + Tq = \frac{Bm\ Va - Bm^2\ w}{Ra\ (1 + sTa)} \qquad (5.7)$$

i.e.

$$\frac{w}{Va} = \frac{Bm - Tq\ Ra\ (1 + sTa)}{Ra\ Bv\ (1 + sTa)\ (1 + sT_L) + Bm^2} \qquad (5.8)$$

This is the transfer function of a separately excited, armature controlled, d.c. motor with torque losses. For many d.c. motors the mechanical time constant dominates and so the armature time constant can be neglected. Thus the system behaves as a first order system and equation 5.8 becomes

$$\frac{w}{Va} = \frac{Bm - Tq\ Ra}{Ra\ Bv\ (1 + sT_L) + Bm^2}$$

$$= \frac{K_1}{1 + sT_1} \tag{5.9}$$

$$\text{where } K_1 = \frac{Bm - Tq\ Ra}{Bm^2 + Ra\ Bv} \tag{5.10}$$

$$\text{and} \quad T_1 = \frac{Ra\ Bv\ T_L}{Bm^2 + Ra\ Bv} = \frac{Ra\ J}{Bm^2 + Ra\ Bv} \tag{5.11}$$

If Bv and Tq are small then this can be approximated by

$$K_1 = \frac{1}{Bm} \quad \text{and} \quad T_1 = \frac{Ra\ J}{Bm^2} \tag{5.12}$$

This is a first order, type zero system. A block diagram representation of the motor is shown in Figure 5.2 and a Bode plot of its frequency response is shown in Figure 5.3.

5.2.2 Input Signal to Wheel Position - Open Loop

Equation 5.9 relates the speed of the motor shaft to the voltage applied to the armature. For the motor to steer the vehicle its output shaft is connected, through a gearbox to the steering wheels. Between the motor shaft and the steering wheels therefore is a gearbox of ratio G and the transfer function between the rate of turn

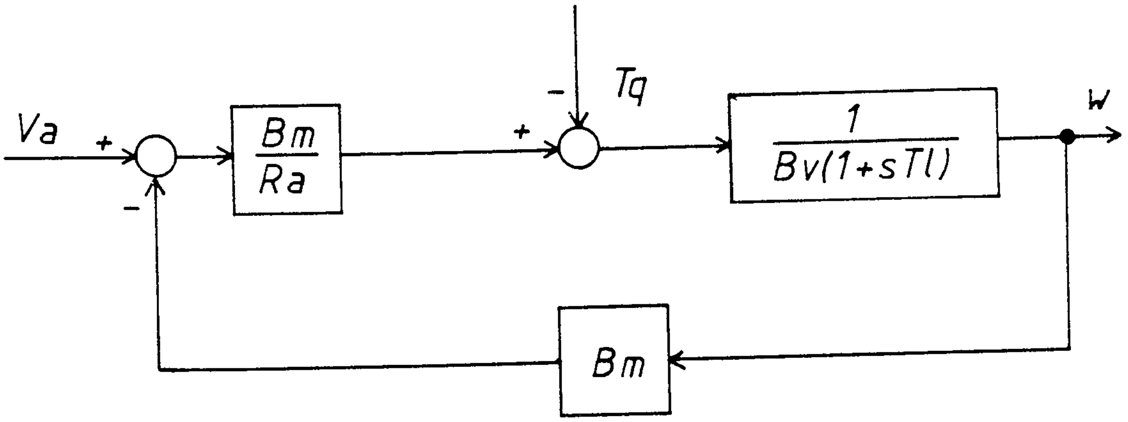


Figure 5.2 -The Separately Excited, Armature Controlled d.c. Motor - Block Diagram

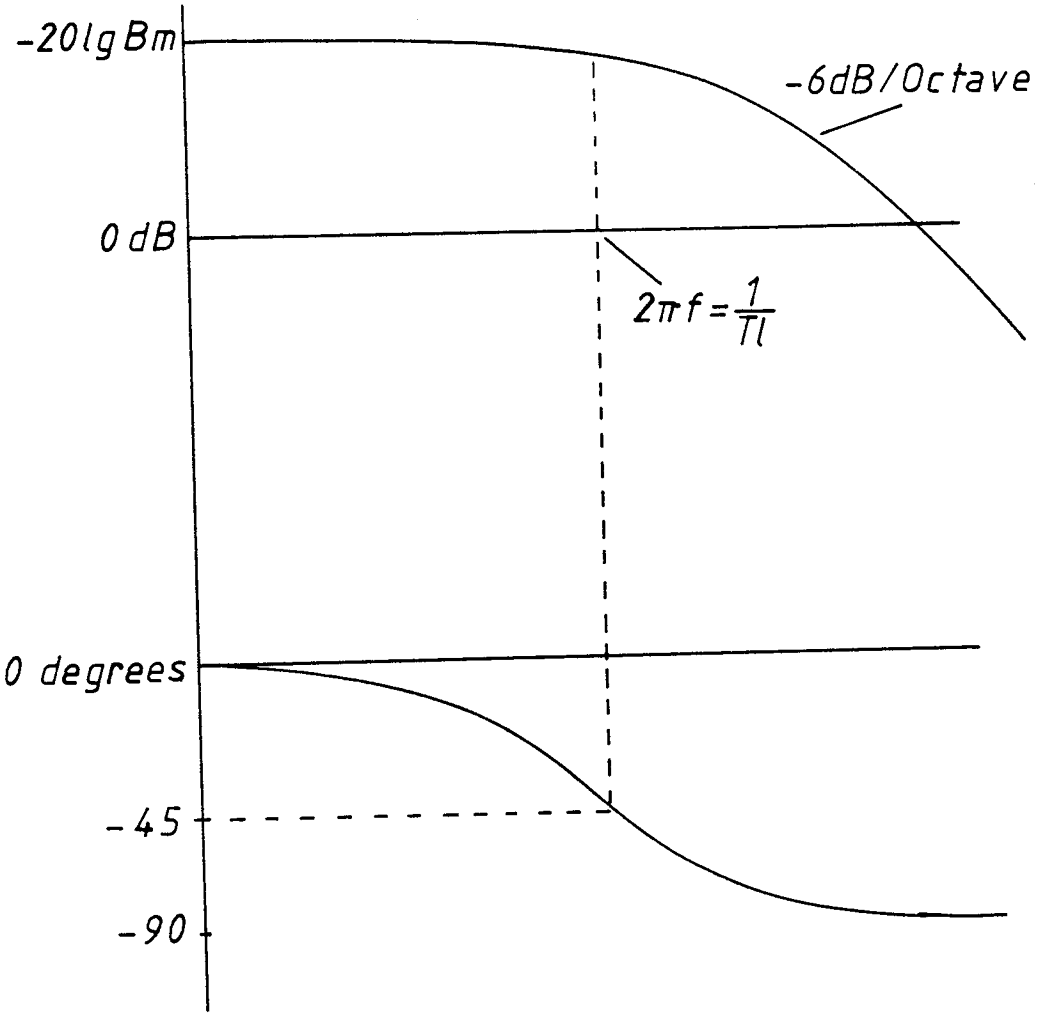


Figure 5.3 - First Order, Type Zero System Bode Plot

of the steering wheels and the angle set on the steering wheels is a simple integration, i.e.

$$\delta = \frac{Gw}{s} \tag{5.13}$$

where δ is the angle set on the steering wheels. If the armature voltage is supplied by some input signal which is subsequently amplified by a gain factor K_2 to provide the actual applied voltage then

$$Va = K_2 Vin \tag{5.14}$$

and the transfer function between the steering angle set on the wheels and the input signal is given by

$$\frac{\delta}{Vin} = \frac{G K_1 K_2}{s (1 + sT_1)} \tag{5.15}$$

where the value of J now includes the moment of inertia of the gearbox, steering linkages and wheels. In practice, because of the gear ratio, the reflected values of these moments of inertia are only small compared to the armature and gearbox moment of inertia and it is this which dominates the mechanical time constant. This is a second order, type one system. A block diagram representation of this part of the system is shown in Figure 5.4 and a bode plot of its frequency response is given in Figure 5.5.

5.2.3 Input Signal to Wheel Position - Closed Loop

In the closed loop configuration, the steering angle is fed back

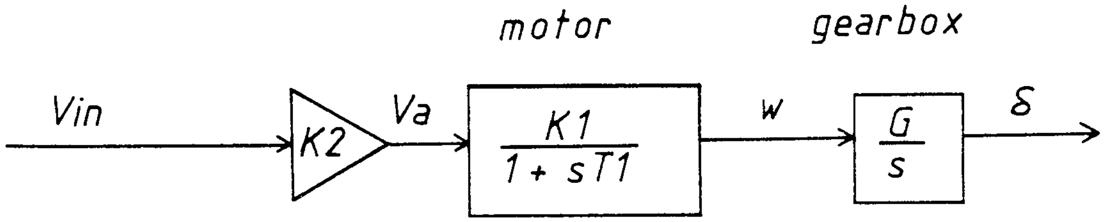


Figure 5.4 - The Steering Control System
Input Signal to Wheel Position
Open Loop Response

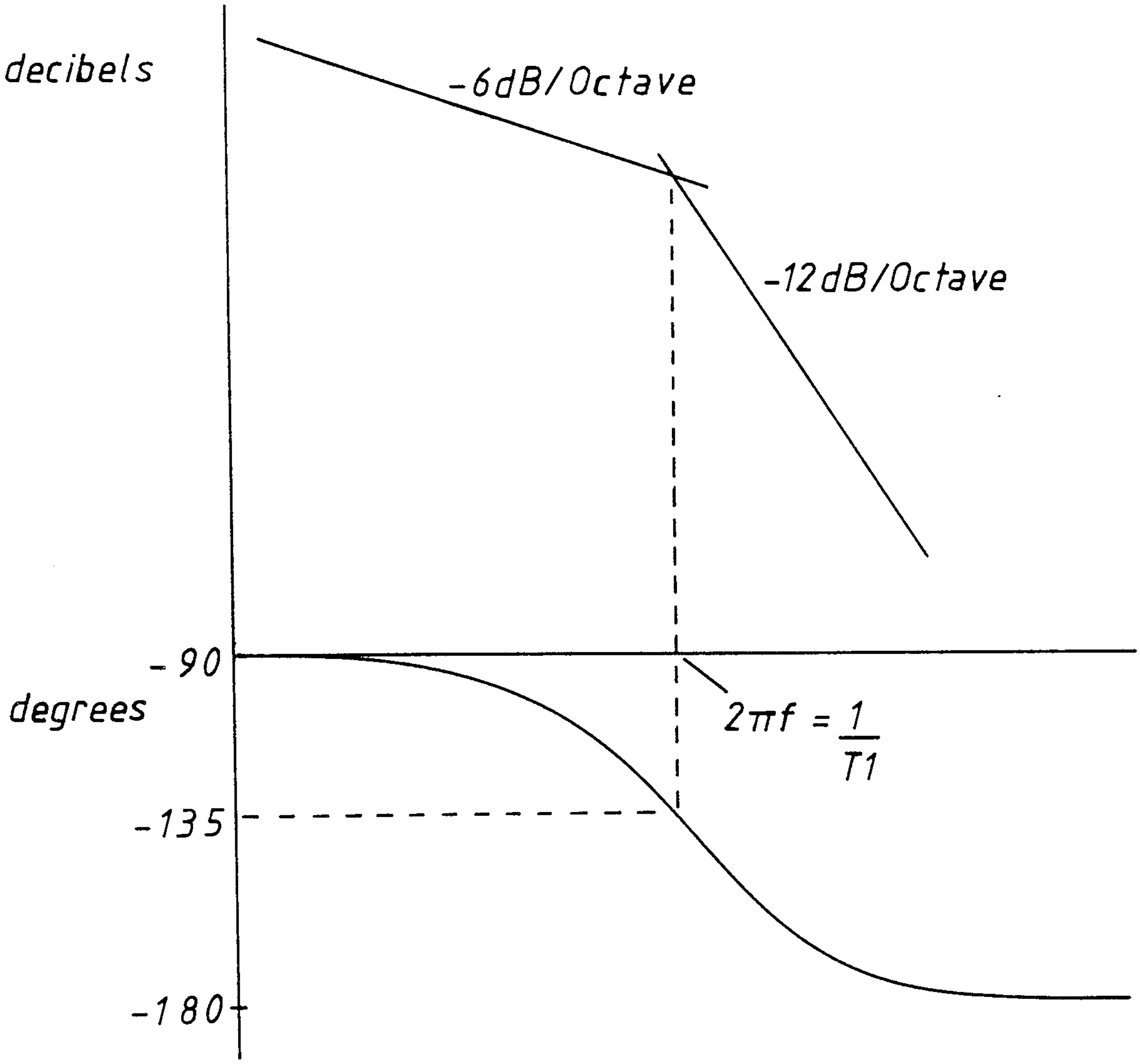


Figure 5.5 - Second Order, Type One System
Bode Plot

and compared with the input signal Vin to provide an error voltage in the system. This error voltage is then amplified to provide the armature voltage which is applied to the motor. For a unity feedback system the closed loop transfer function C(s) is given by

$$C(s) = \frac{G(s)}{1 + G(s)} \tag{5.16}$$

where G (s) is the open loop transfer function[46]. Substituting equation 5.15 for G (s) gives the steering motor closed loop position control response as

$$\frac{\delta}{Vin} = \frac{G K_1 K_2/s\ (1 + sT_1)}{1 + G K_1 K_2/s\ (1 + sT_1)} = \frac{Ka}{s^2 + as + Ka} \tag{5.17}$$

where $Ka = G K_1 K_2 / T_1$ and $a = 1 / T_1$.

The closed loop response of a generalised second order system is given by[46]

$$C(s) = \frac{Wn^2}{s^2 + 2 \zeta\, Wn\, s + Wn^2} \tag{5.18}$$

where ζ is the system damping ratio and Wn is the natural frequency of the system.

Equating expressions 5.17 and 5.18 gives

$$Wn = \sqrt{Ka} \tag{5.19}$$

$$\zeta = \frac{a}{2\sqrt{Ka}} \tag{5.20}$$

Thus the system bandwidth and damping ratio can be altered by varying the gain factor. This allows the speed of response of the system to an angle demand at its input to be made as fast as possible without incurring too much overshoot. This is a second order, type zero system. The system block diagram is given in Figure 5.6 and its Bode plot is given in Figure 5.7.

The size of the resonant peak Mpw and the ratio of the resonant frequency of the system to the natural frequency of the system Wr/Wn are both functions of the damping ratio ζ. For values of ζ below 0.7 they are given by[46]

$$Mpw = (2\zeta\sqrt{1-\zeta^2})^{-1} \qquad \zeta < 0.7 \qquad (5.21)$$

$$Wr/Wn = \sqrt{1-2\zeta^2} \qquad \zeta < 0.7 \qquad (5.22)$$

and for ease of reference these are plotted graphically in Figure 5.8.

5.3 VEHICLE LATERAL RESPONSE - THE THEORY

Figure 5.9 shows a four wheeled vehicle travelling in a direction such that the front wheels are the steered wheels and the rear wheels on a fixed axis are the driven wheels. It is assumed that the front wheels are steered in such a manner that the centre of rotation for each wheel lies at the same point on the line through the fixed axis and perpendicular to the centre line of the vehicle. This requires that slightly different angles be put on each wheel,

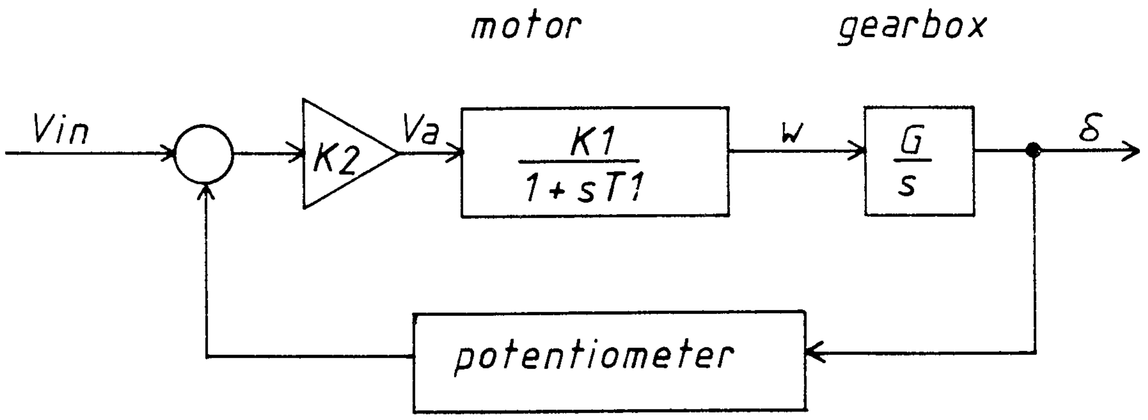


Figure 5.6 - The Steering Control System closed loop angle demand system

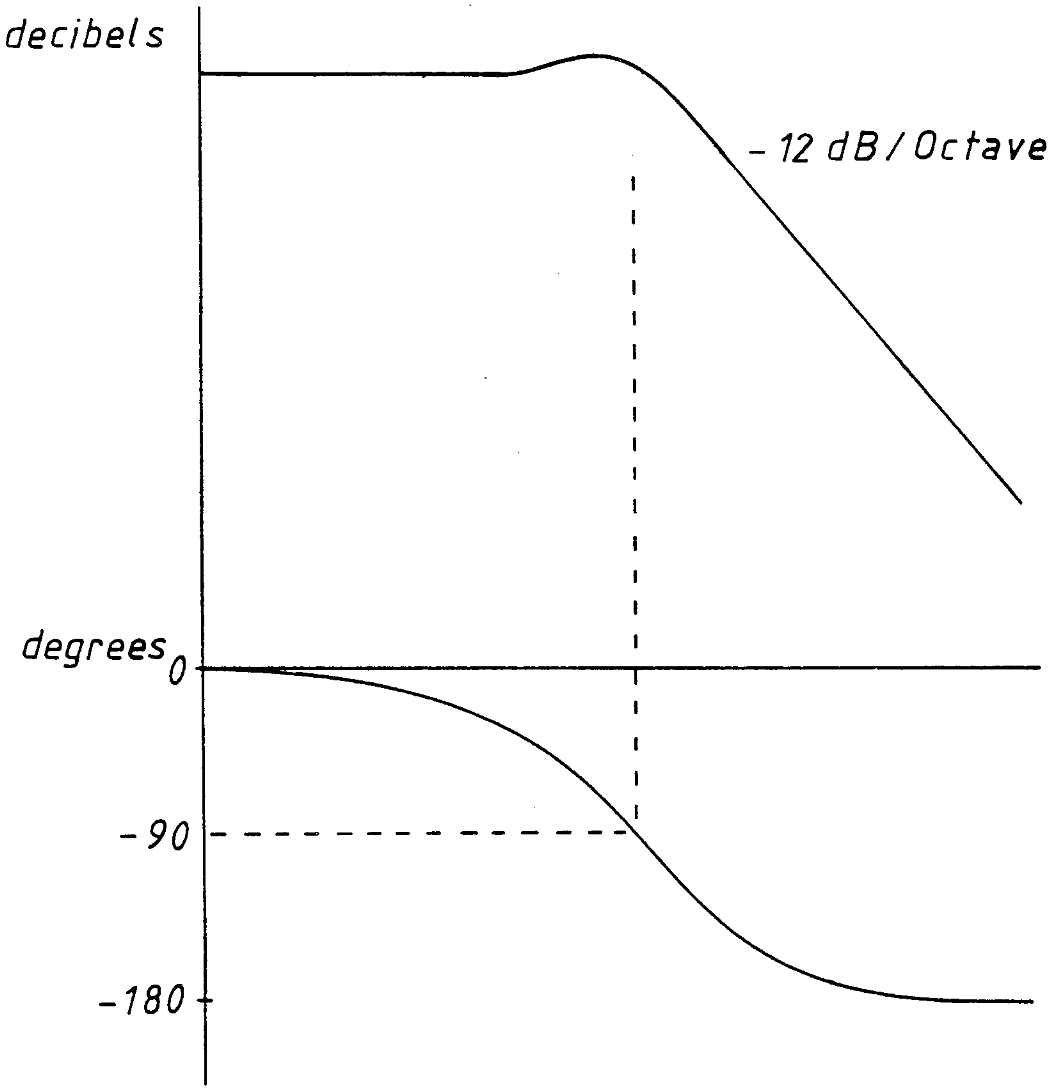


Figure 5.7 - Second Order, Type Zero System Bode Plot

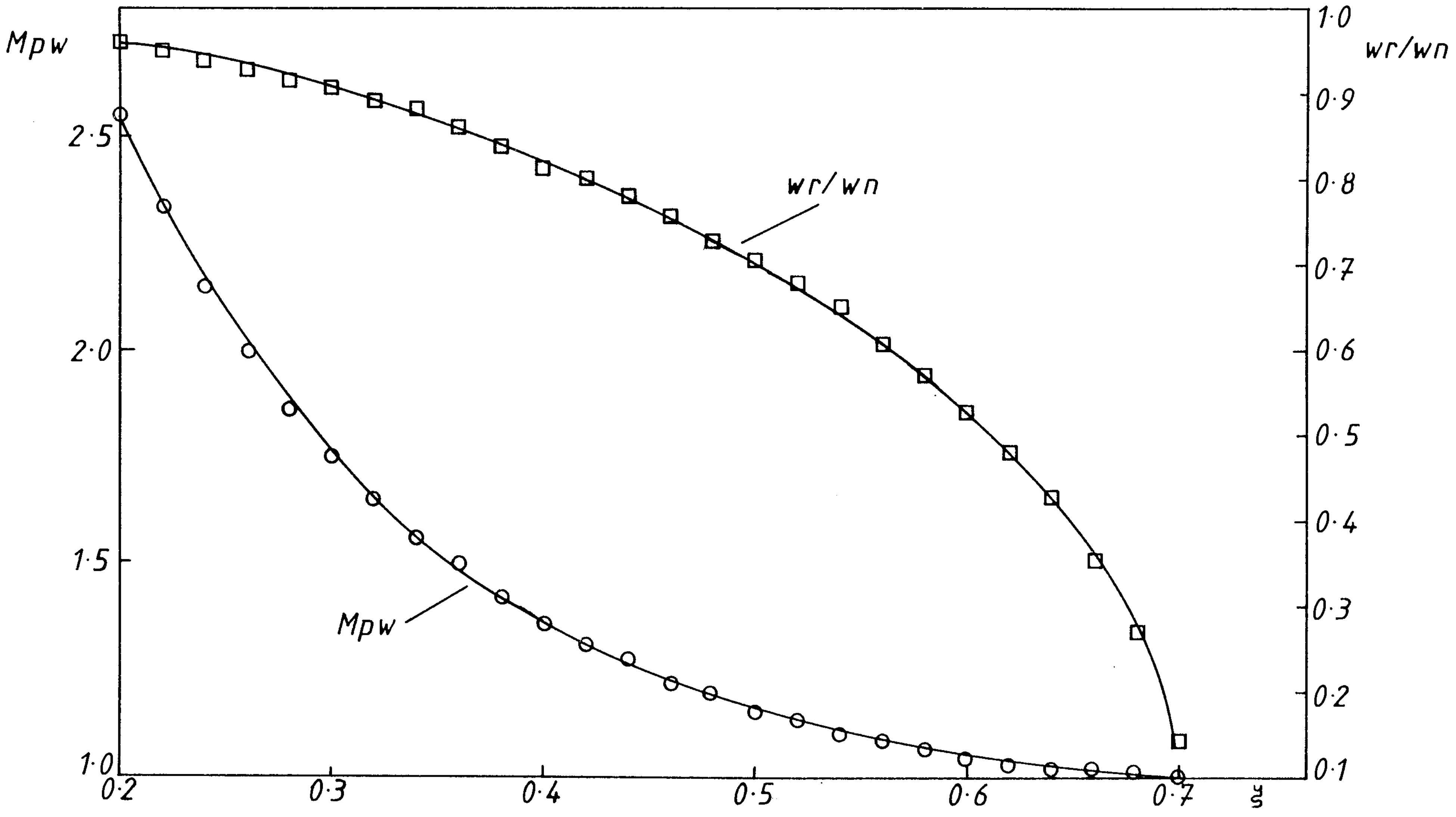


Figure 5.8 - A Plot of Mpw & wr/wn vs. ξ for a Second Order System

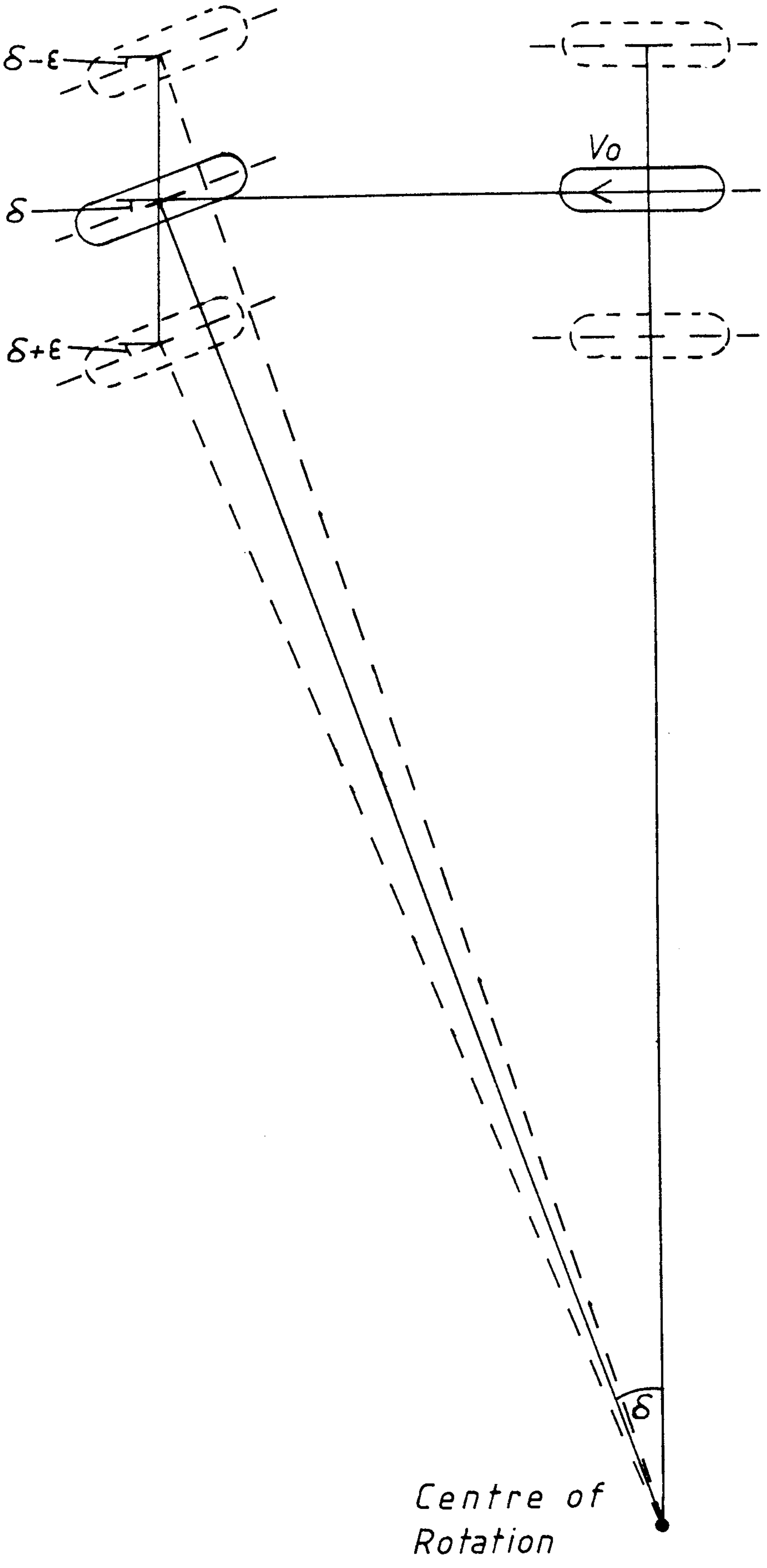


Figure 5.9 - The Two Wheeled Vehicle Model

and allows the angle of steer to be referred, as a single angle, to the centre of the front axle. This system is known as the Ackermann system of steering (see Figure 5.9). It is further assumed that the differential speeds required on the driven wheels when cornering are negligible compared with the speed at which the wheels are driven. This allows the speed of the vehicle to be referred to the centre of the back axle even when cornering. Thus the vehicle can be collapsed into the two wheeled model shown in Figure 5.9 by the solid line tyres.

Finally it is assumed that at low speeds ($\leqq 1\ \mathrm{ms}^{-1}$) dynamic effects of the vehicle when cornering are negligible and that the vehicle lateral response is due solely to kinematic effects. Private consultation with Professor J. R. Ellis, Director of the Advanced School of Automobile Engineering, Cranfield, suggested a boundary between kinematics and dynamics of a lateral acceleration of $1\ \mathrm{ms}^{-2}$ for over one second. Above this boundary dynamic effects become increasingly important whilst below it they are negligible. For a steady state turn of radius r, the lateral acceleration a_1 is given by

$$a_1 = \frac{Vo^2}{r} \tag{5.23}$$

where Vo is the vehicle velocity. For speeds less than $1\ \mathrm{ms}^{-1}$, a_1 will always be less than $1\ \mathrm{ms}^{-2}$, as long as r is less than 1 m and radii of curvature are seldom smaller than this.

To investigate the movement of a point P lying on the vehicle centre line at a distance u in front of the back axle, its movement will be referred to Cartesian axes system. This is shown in Figure 5.10 where initially the vehicle centre line is parallel to the x-axis and the point in consideration lies at the system origin. For a constant angle of steer the point will move along the arc of a circle and its movement can be traced by considering the velocity vector of that point. Each point along the vehicle centre line will move on the arc of a circle, each of different radii, and this will give rise to different tangential velocities for each point. The further the point from the back axle, the greater its velocity must be, since over a complete revolution it travels further than a point closer in to the back axle, i.e. around a larger circle. Following Ellis[55] we can decompose the velocity vector into components parallel and perpendicular to the vehicle centre line, such as U and V in Figure 5.10. Since the vehicle is a rigid structure and neither elongates nor compresses when cornering, the components parallel to the vehicle centre line must all be equal. Thus differences in velocity for different points must be met by differences in the velocity component perpendicular to the vehicle centre line. This simply states that the further forward a point is, the further it moves in the y direction for a given vehicle speed and steering angle. Again, since the vehicle is a rigid structure, all points must move with the same angular velocity when cornering. This angular velocity w, is given by

$$w = \frac{Vu}{Ru} \tag{5.24}$$

where Vu is the velocity of any point and Ru is the radius of curvature at that point.

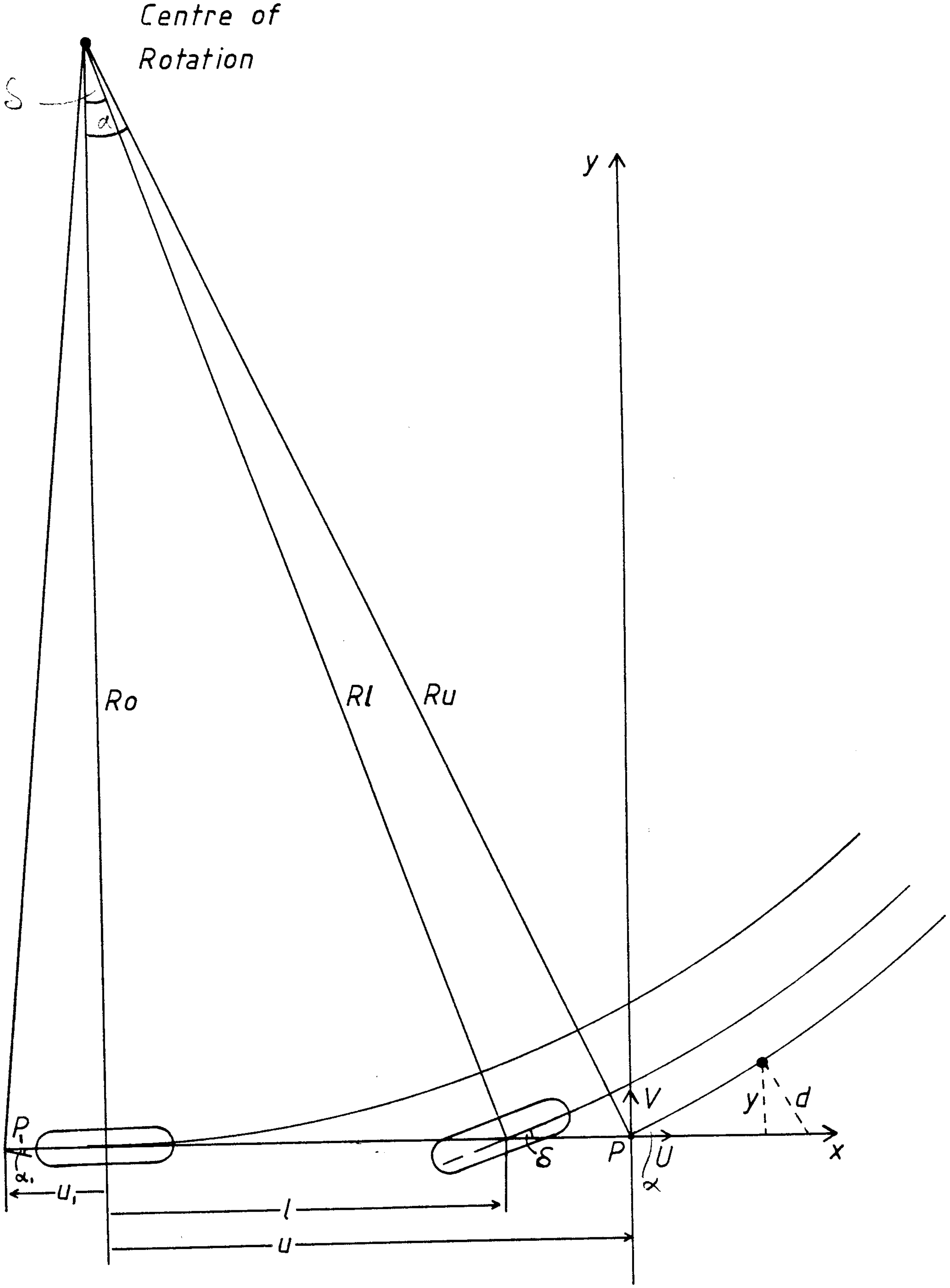


Figure 5.10–The Geometry of the Vehicle Movement in a forwards direction

At the back axle u = 0 and the values of Vu and Ru are known. The velocity Vu is simply the vehicle velocity Vo and the radius of curvature of the back axle Ro is given from the geometry of Figure 5.10 by

$$Ro = \frac{l}{\tan \delta} \qquad (5.25)$$

where l is the vehicle wheelbase and δ is the steering angle.

Thus the angular velocity w is given by

$$w = \frac{Vo \tan \delta}{l} \qquad (5.26)$$

The velocity Vu of the point P at a distance u from the back axle is given by equation 5.24. The angle between the velocity vector and the vehicle centre line is the angle α as marked on Figure 5.10 both at the point P and at the centre of rotation. Thus the components U and V are given by

$$U = Vu \cos \alpha = w\, Ru \cos \alpha \qquad (5.27)$$

$$\text{and} \quad V = Vu \sin \alpha = w\, Ru \sin \alpha$$

Now from Figure 5.10

$$Ru \cos \alpha = Ro$$

$$\text{and} \quad Ru \sin \alpha = u \qquad (5.28)$$

Thus substituting in equation 5.27 gives

$$U = w \ Ro = Vo$$

and $$V = w \ u = \frac{Vo \ u \tan \delta}{l} \qquad (5.29)$$

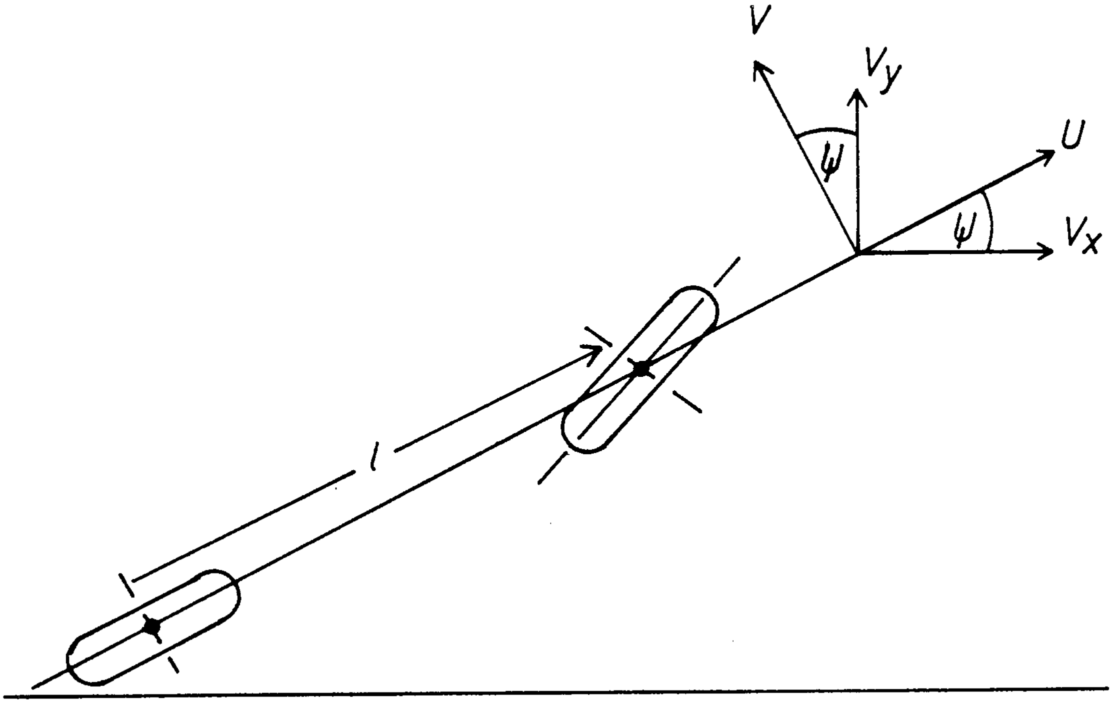
Thus the component parallel to the vehicle centre line is constant along the length of the centre line and the perpendicular component increases from zero as the point moves away from the back axle.

As the various points on the vehicle move along the arcs of their radii of curvature, the different lateral components of their tangential velocities means that points further away from the back axle will move further out from the x-axis than points nearer the back axle. This will lead to a change in attitude between the vehicle centre line and the x-axis. Thus the velocity of the point P in the y direction, which was initially the component of velocity perpendicular to the vehicle centre line, will now be the sum of the components of the two velocity vectors U and V in the y direction. Thus referring to Figure 5.11, the velocity in the y direction Vy, is given by

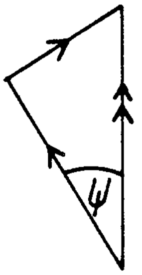
$$Vy = U \sin \psi + V \cos \psi \qquad (5.30)$$

where ψ is the vehicle attitude, i.e. the angle between the vehicle centre line and the x-axis. The vehicle attitude ψ is simply the angle turned through by the vehicle in response to an applied angular velocity w. Thus ψ is given by

$$\psi = \int w \ . \ dt = \int \frac{Vo \tan \delta}{l} \ . \ dt \qquad (5.31)$$

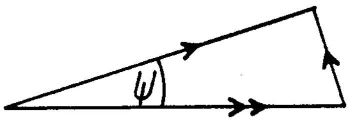


a) Diagram of the Vehicle Position



$$V_y = U \sin\psi + V \cos\psi$$

b) Triangle of Velocities for Vy



$$V_x = U \cos\psi + V \sin\psi$$

c) Triangle of Velocities for Vx

Figure 5.11 - Velocity Components in the x & y Directions

The lateral deviation of the vehicle from the y-axis produced by an applied angle δ on the steering is then given by the time integral of the lateral velocity, i.e.

$$y = \int Vy \, . \, dt = \int (U \sin \psi + V \cos \psi) \, . \, dt \tag{5.32}$$

and from a similar analysis

$$x = \int (U \cos \psi + V \sin \psi) \, . \, dt \tag{5.33}$$

Now the lateral position sensor is carried on the vehicle, and it measures a deviation perpendicular to the vehicle centre line. Thus referring to Figure 5.10 where the wire is a straight line running along the x-axis, the measured deviation is d. The relationship between d and y is given by

$$d = \frac{y}{\cos \psi} \tag{5.34}$$

i.e.

$$d = \frac{1}{\cos \psi} \int (U \sin \psi + V \cos \psi) \, . \, dt \tag{5.35}$$

Taking the 1/cos ψ multiplier inside the integral gives

$$d = \int (U \tan \psi + V) \, . \, dt \tag{5.36}$$

Thus the measured deviation of the point P, when an angle δ is put on the steering and the wire continues in a straight line is due to two components: one is V, the lateral velocity of the point P; and the other is U tan ψ, which is the contribution due to the attitude of the vehicle to the initial datum.

Figure 5.12 shows the same vehicle in the situation where the vehicle is travelling in a direction such that the rear wheels are now the steered wheels and the front wheels on a fixed axis are the driven wheels, i.e. the vehicle is travelling backwards. In considering the movement of a point P' lying on the vehicle centre line at a distance u' in front of the fixed axle, a comparison of Figures 5.10 and 5.12 shows that the mathematics of both situations is almost exactly the same. The only difference now is that referred to the x-axis, the angles α and δ are in the opposite sense in Figure 5.12 and in the same sense in Figure 5.10. Referring to Figure 5.10, however, it can be noted that the point P_1 lying behind the fixed axis has an initial angle α_1, which is in the opposite sense to the angles α and δ. The negative value of α_1 for the point P_1 simply means that its velocity component perpendicular to the vehicle centre line is in the opposite direction to that of points in front of the fixed axle. This velocity is still given by equation 5.29 if it is realised that u is a negative quantity. This also applies to l in Figure 5.12. Thus the analysis remains the same if it is realised that the distance from the fixed axle is a signed quantity. The positive direction is given as the direction in which the vehicle is travelling. Thus when the steering axis is in front of the fixed axis (Figure 5.10) a positive steering angle must be applied to give a positive displacement, whereas when the steering axis is behind the fixed axis (Figure 5.12) a negative steering angle must be applied to give the same positive displacement. These negative values of the perpendicular component of the velocity of points behind the fixed axle simply reflect the facts that when cornering, points behind the fixed axle swing out and when steering from the rear, the steering

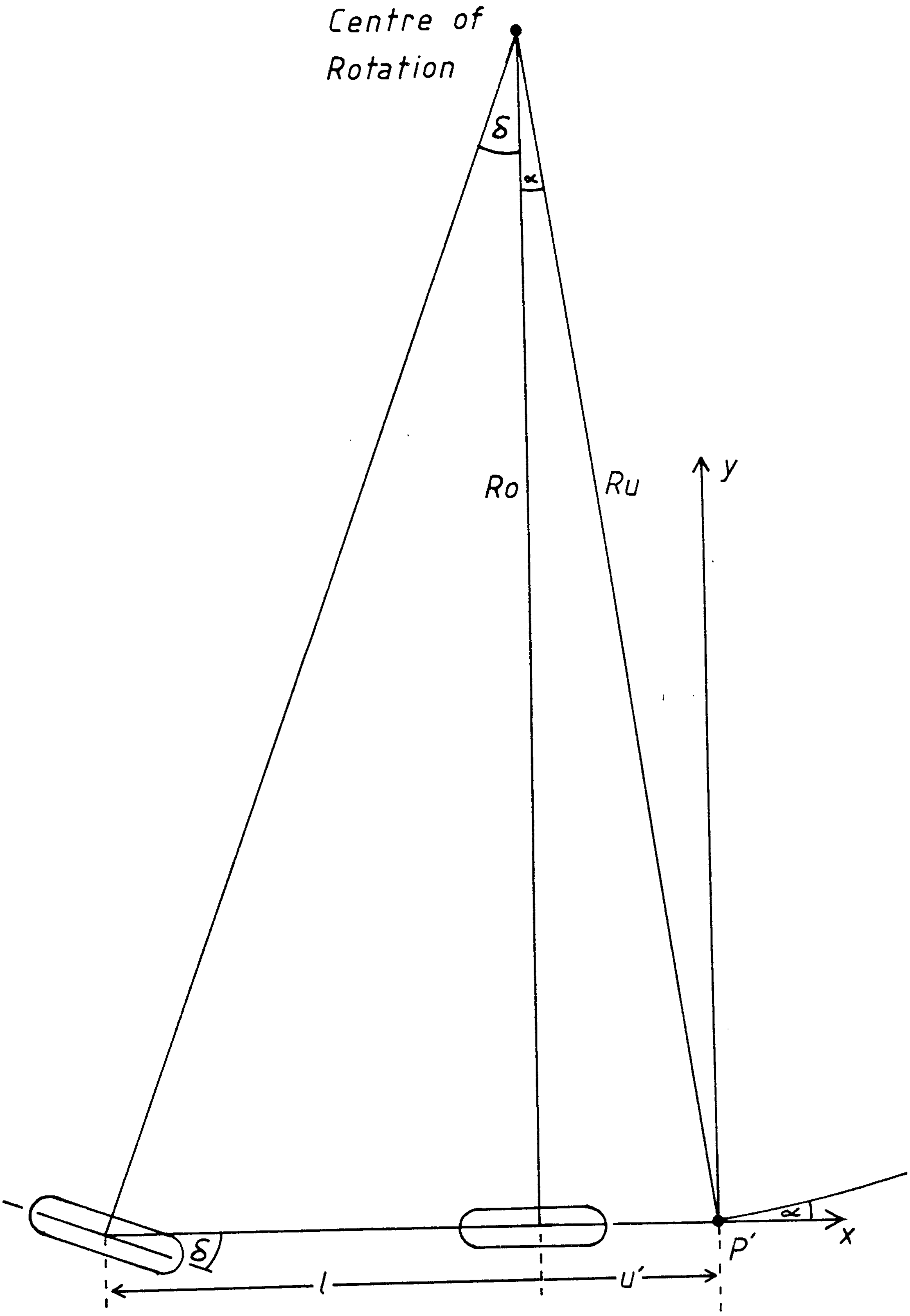


Figure 5.12 - The Geometry of the Vehicle Movement in a reverse direction

angle must be supplied in the opposite sense as to that required when steering from the front.

Thus using equations 5.29, 5.31 and 5.36 the measured deviation of the point P can be evaluated in terms of the vehicle wheelbase, the velocity of the vehicle, the steering angle, and the location of the point P relative to the back axle, i.e.

$$y = \mathrm{Fn}\ (1, Vo, \delta, u) \tag{5.37}$$

and for a given application 1 and u will be fixed such that

$$y = \mathrm{Fn}\ (Vo, \delta) \tag{5.38}$$

and the lateral displacement for a given vehicle depends only on the vehicle speed and the steering angle.

5.4 LATERAL POSITION SENSOR - THE THEORY

The electromagnetic lateral position sensor, as mentioned in Section 2.3, consists of two coils mounted on the vehicle and a guide wire buried to a depth of a few centimetres in the ground. An alternating current is passed down the wire, and this gives rise to a time varying but spatially constant field. The shape of this field is found by evaluating the Biot-Savart integral for this form of conductor and is found to be a series of concentric field lines centered on the wire (see Figure 5.13)[48] .

The magnetic flux density B is given by:

$$B = \frac{\mu_o\, i}{2\,\pi\, a} \tag{5.39}$$

where i is the instantaneous value of the current in the wire

a is the radial distance from the wire

and μ_o is the permeability of free space

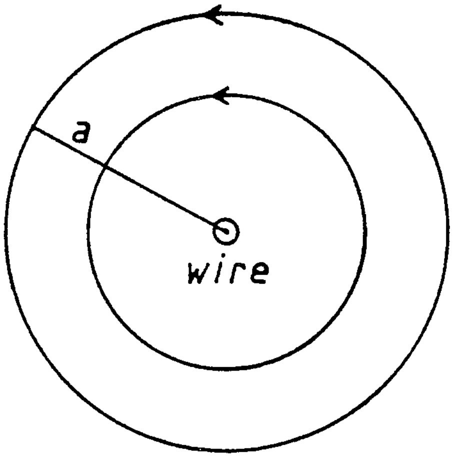


Figure 5.13 - The Magnetic Field of the Guide Wire

Figure 5.14 shows a thin coil in the magnetic field of the wire. The coil is of a uniform circular cross-section of radius r and is at a height h above the wire with the axis of the coil horizontal. Cartesian axes x and y are shown with the origin at the coil centre.

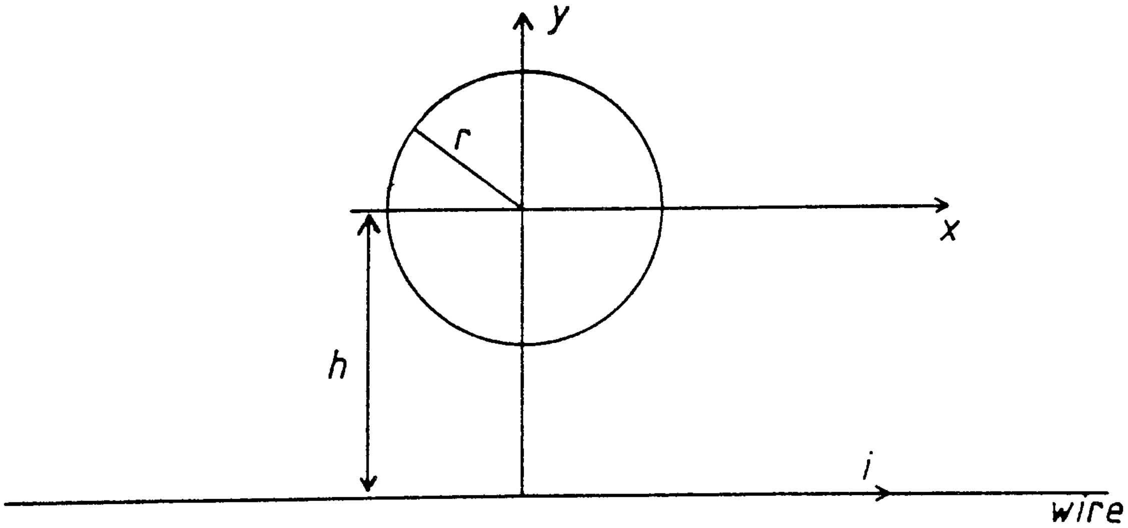


FIGURE 5.14: A THIN COIL IN THE MAGNETIC FIELD OF THE WIRE

The equation of the coil is $x^2 + y^2 = r^2$ giving $x = \pm \sqrt{r^2 - y^2}$ Thus the difference between the two points A and A' lying on the circumference of the coil on a line parallel to the x-axis (Figure 5.15) is given by

$$\delta x = 2\sqrt{r^2 - y^2} \tag{5.40}$$

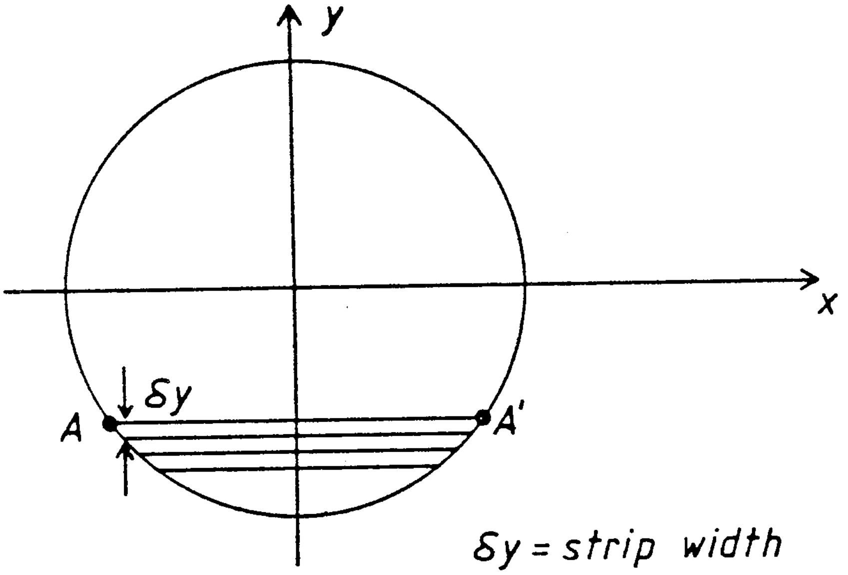


Figure 5.15 - Elemental Coil Segments

Dividing the coil into segments parallel to the x-axis and hence parallel to the wire as well, then assuming the strip width δy is small, the flux density through each elemental segment will be constant over the whole of the segment. The area δS of a segment is given by

$$\delta S = \delta x \,.\, \delta y = 2\,\delta y\sqrt{r^2 - y^2} \tag{5.41}$$

and the magnetic flux $\delta\Phi_H$ crossing each segment of a horizontal coil is given by

$$\delta\Phi_H = \underline{B} \,.\, \underline{\delta S} = Bn \,.\, \delta S \tag{5.42}$$

where $B_n = \underline{B} \cos \theta$ (see Figure 5.16) and is the normal component of the magnetic flux density at the segment. Figure 5.16 shows a side-on view of the coil in the magnetic field of the guide wire. The equations of the lines of magnetic field strength are given by

$$z^2 + (h + y)^2 = a^2 \tag{5.43}$$

where a is the radial distance of the segment from the guide wire.

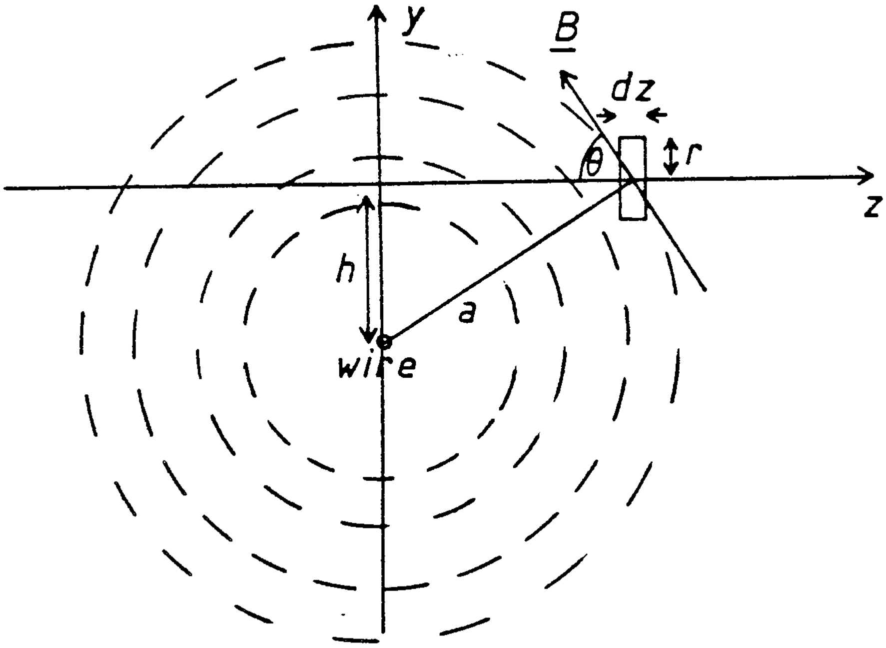


Figure 5.16 - A Coil in the Wire's Magnetic Field - Transverse View

The slope of the magnetic field at any point is found by taking the derivative of equation 5.43 with respect to z i.e.

$$2\,z + 2\,(h + y) \cdot \frac{dy}{dz} = 0 \tag{5.44}$$

or

$$\frac{dy}{dz} = \frac{-\,z}{(h + y)} = \tan\,(180 - \theta) = -\tan\theta \tag{5.45}$$

where θ is defined as in Figure 5.16.

Thus $\tan\theta = \dfrac{z}{(h + y)}$ and $\cos\theta = \dfrac{h + y}{\sqrt{z^2 + (h + y)^2}}$ (5.46)

From equation 5.39 the magnetic field induction $\underline{B}$ at a distance a from the wire is given by

$$\underline{B} = \frac{\mu o\ i}{2\pi a} \qquad (5.47)$$

and from equation 5.43, a is given by

$$a = \sqrt{z^2 + (h + y)^2} \qquad (5.48)$$

Thus the normal component of the flux density to the coil at the point (y, z) is given by

$$Bn = \underline{B}\cos\theta = \frac{\mu o\ i\ (h + y)}{2\pi\ (z^2 + (h + y)^2)} \qquad (5.49)$$

and equation 5.42 becomes

$$\delta\Phi_H = \frac{\mu o\ i\ (h + y)\ \sqrt{r^2 - y^2}\ .\ \delta y}{\pi\ (z^2 + (h + y)^2)} \qquad (5.50)$$

The total flux crossing a coil with a horizontal axis is found by integrating equation 5.50 between the limits y = -r and y = r, i.e.

$$\Phi_H = \int Bn\ .\ \delta S = \int_{-r}^{r} \frac{\mu o\ i\ (h + y)\ \sqrt{r^2 - y^2}\ .\ dy}{\pi\ (z^2 + (h + y)^2)} \qquad (5.51)$$

A similar analysis for a coil with its axis vertical (which can be found in Appendix A) gives

$$\Phi_V = \int_{c-r}^{c+r} \frac{\mu o\ i\ z\ \sqrt{r^2 - (z - c)^2}\ .\ dz}{\pi\ (z^2 + h^2)} \qquad (5.52)$$

The form of these functions are shown in Figure 7.2 which shows the normalised flux distribution for both horizontal and vertical search coils versus distance.

For a finite coil placed horizontally in the wire's magnetic field with n turns per unit length, the flux crossing a length dz is Φ_H n. dz, assuming that dz is small enough for Φ_H to be constant along its length. For a coil of length l wound round a ferrite core of permeability μr the flux cutting the whole coil is given by

$$\Phi = \int_{o}^{l} \int_{-r}^{r} \frac{\mu o \ \mu r \ ni \ (h + y) \sqrt{r^2 - y^2} \ . \ dy \ . \ dz}{\pi \ (z^2 + (h + y)^2)} \qquad (5.53)$$

The current in the wire is an alternating current i = Im sin wt where Im is the maximum value of the current. This gives a flux of the form

$$\Phi = \Phi m \ . \ \sin wt \qquad (5.54)$$

where Φm is the maximum value of the flux, and is found by evaluating equation 5.53 for i = Im. The emf induced in the coil due to the time varying flux Φ is given by Neumann's law as[48]

$$E = \frac{-\partial \Phi}{\partial t} = w \ \Phi \ m \cos wt = Em \cos wt \qquad (5.55)$$

where Em = w Φ m is the maximum value of the induced emf. Thus

$$Em = \int_{o}^{l} \int_{-r}^{r} \frac{w \ \mu o \ \mu r \ nIm \ (h + y) \sqrt{r^2 - y^2} \ . \ dy \ . \ dz}{\pi \ (z^2 + (h + y)^2)} \qquad (5.56)$$

A programme to evaluate Em on this basis was written and results from it are given in Chapter 7.

5.5 STEERING MOTOR, GEARBOX AND LOAD - THE MODEL

The mathematics of Section 5.2 were used as the basis of a model which was run on a digital computer. To do this the continuous nature of the equations developed must be approximated by discrete equations. Thus the derivatives of the continuous system, as represented by the Laplace operator s, must be replaced with finite difference equations. Then the system response can be evaluated at discrete moments in time, and these moments must be close enough together to provide a reasonable approximation to the continuous system. The spacing of these moments is known as the sampling time or sampling period of the system. The sampling time must theoretically be less than half the value of the smallest system time constant. In practice it is found the sampling time must be about one tenth of the smallest system time constant to avoid instability in the discrete approximation. This section will develop the discrete form of the mathematics for the motor, gearbox and load.

5.5.1 Armature Volts to Motor Speed

The two equations governing the operation of the armature controlled, separately excited d.c. motor are equations 5.3 and 5.5, i.e.

$$Va - Ra\ Ia - sLa\ Ia - Vg = 0 \qquad (5.3\ \text{repeated})$$

and

$$T = J_L\ \alpha + Bv.w + Tq \qquad (5.5\ \text{repeated})$$

Rearranging these equations to place the differential term of each equation on the right and noting that α = sw gives

$$sLa\ Ia = La\ \dot{Ia} = -Ra\ Ia - Bm.w + Va \qquad (5.57)$$

and

$$sJ_L\ w = J_L\ \dot{w} = T - Bv.w - Tq \qquad (5.58)$$

where the dot above a quantity indicates differentiation of that quantity with respect to time. Dividing through each equation by the constant term and substituting for T from equation 5.1 and Vg from equation 5.2 gives

$$\dot{Ia} = \left(\frac{-Ra}{La}\right) Ia + \left(\frac{-Bm}{La}\right) w + \left(\frac{1}{La}\right) Va \qquad (5.59)$$

and

$$\dot{w} = \left(\frac{Bm}{J_L}\right) Ia + \left(\frac{-Bv}{J_L}\right) w + \left(\frac{-1}{J_L}\right) Tq \qquad (5.60)$$

This use of a set of first order differential equations to describe the dynamics of a system is known as the state space method. If we pick Ia and w as the state variables x_1 and x_2[46,56] then we can represent equations 5.59 and 5.60 in the matrix form below

$$\underline{\dot{x}} = \underline{A}\ \underline{x} + \underline{B}\ \underline{u} \qquad (5.61)$$

where $\underline{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} Ia \\ w \end{bmatrix}$ and is the state vector matrix (5.61.1)

$$\underline{A} = \begin{bmatrix} -Ra/La & -Bm/La \\ Bm/J_L & -Bv/J_L \end{bmatrix} \qquad (5.61.2)$$

$$\underline{B} = \begin{bmatrix} 1/La & 0 \\ 0 & -1/J_L \end{bmatrix} \qquad (5.61.3)$$

and $\underline{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} Va \\ Tq \end{bmatrix}$ and is the matrix of input signals (5.61.4)

This compact form of notation is known as the system vector differential equation. It is a continuous representation of the system dynamics. To write it as a discrete difference equation, the continuous first order differential is approximated by

$$\dot{\underline{x}} = \frac{\underline{x}\,(k+1) - \underline{x}\,(k)}{T} \quad \text{where } k = 0, 1, 2, \ldots \qquad (5.62)$$

where T is the sampling period of the discrete system. Substituting into equation 5.61 gives

$$\frac{\underline{x}\,(k+1) - \underline{x}\,(k)}{T} = \underline{A}\,\underline{x}\,(k) + \underline{B}\,\underline{u}\,(k) \qquad (5.63)$$

i.e.

$$\underline{x}\,(k+1) = (T\,\underline{A} + \underline{I})\,\underline{x}\,(k) + T\,\underline{B}\,\underline{u}\,(k) \qquad (5.64)$$

where $\underline{I}$ is the identity matrix. Thus the discrete form of the system vector differential equation is given by

$$\underline{x}\,(k+1) = \underline{\psi}\,\underline{x}\,(k) + T\,\underline{B}\,\underline{u}\,(k) \qquad (5.65)$$

where $\underline{\psi} = T\,\underline{A} + \underline{I}$ (5.65.1)

Substituting the values of $\underline{A}$ and $\underline{B}$ from equation 5.61 gives

$$x_1(k+1) = \psi_1 x_1(k) + \psi_2 x_2(k) + T B_1 u_1(k) \qquad (5.66)$$

$$\text{where } \psi_1 = 1 - \frac{T \cdot Ra}{La} \qquad (5.66.1)$$

$$\psi_2 = - \frac{T \cdot Bm}{La} \qquad (5.66.2)$$

$$\text{and } B_1 = \frac{1}{La} \qquad (5.66.3)$$

$$\text{and } x_2(k+1) = \psi_3 x_1(k) + \psi_4 x_2(k) + T B_2 u_2(k) \qquad (5.67)$$

$$\text{where } \psi_3 = \frac{T \cdot Bm}{J_L} \qquad (5.67.1)$$

$$\psi_4 = 1 - \frac{T \cdot Bv}{J_L} \qquad (5.67.2)$$

$$\text{and } B_2 = \frac{-1}{J_L} \qquad (5.67.3)$$

These equations are the state space equations (or equations of state) for a separately excited, armature controlled d.c. motor. They were implemented as a computer programme and the results from it are considered in Chapter 7.

If the load time constant dominates then the armature inductance can be neglected and equation 5.3 becomes

$$Va = Ra\ Ia + Bm\ w \qquad (5.68)$$

i.e.

$$Ia = \frac{Va - Bm \cdot w}{Ra} \qquad (5.69)$$

Substituting T = Bm.Im in equation 5.58 using this value of Ia gives

$$J_L \dot{w} = \frac{Bm . Va - Bm^2 . w}{Ra} - Bv . w - Tq \qquad (5.70)$$

i.e.

$$\dot{w} = \left(\frac{-Bv}{J_L} - \frac{Bm^2}{J_L . Ra}\right) w + \left(\frac{Bm}{J_L . Ra}\right) Va + \left(\frac{-1}{J_L}\right) Tq \qquad (5.71)$$

Replacing the continuous differential $\dot{w}$ with the discrete approximation of equation 5.62 gives

$$x_1 (k + 1) = \psi_1 x_1 (k) + T B_1 u_1 (k) + T B_2 u_2 (k) \qquad (5.72)$$

where $x_1 = w$ (5.72.1)

$$\psi_1 = 1 - \frac{T . Bv}{J_L} - \frac{T . Bm^2}{J_L . Ra} \qquad (5.72.2)$$

$$B_1 = \frac{Bm}{J_L Ra} \qquad (5.72.3)$$

$$B_2 = \frac{-1}{J_L} \qquad (5.72.4)$$

$\underline{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} Va \\ Tq \end{bmatrix}$ is the input signal matrix. (5.72.5)

This is the discrete form of the system vector equation with a single variable and has been implemented as a computer programme.

The main advantage of this single variable representation against the two variable representation is an increase in sample time. The load time constant is always much larger than the motor electrical time constant and so if the electrical time constant is neglected the system sample time can be much increased. This makes the programme much faster to run. Another advantage is a reduction in model complexity and this leads to a more efficient programme. The results from this single variable programme are considered and compared with the two variable programme in Chapter 7.

5.5.2 Input Signal to Wheel Position - Open Loop

Between the motor shaft and the steering wheel is a gearbox of ratio G (Figure 5.4). Thus the rate of turn of the steering wheels is given by

$$\dot{\delta} = G w = G x_1 \tag{5.73}$$

where δ is the angle on the steering wheels. Using equation 5.62 to approximate the derivative and writing $\delta = x_2$ gives

$$\begin{aligned} x_2(k+1) &= T G x_1(k) + x_2(k) \\ &= \psi_4 x_1(k) + x_2(k) \end{aligned} \tag{5.74}$$

where

$$\psi_4 = T.G \tag{5.74.1}$$

Referring to Figure 5.4, the system input is now Vin, and this is amplified by a factor K_2 before being supplied to the motor and so the value of B_1 in equation 5.72 is now given by

$$B_1 = \frac{K_2 \cdot Bm}{J_L \cdot Ra} \qquad (5.75)$$

and the input signal matrix $\underline{u}$ becomes

$$\underline{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} Vin \\ Tq \end{bmatrix} \qquad (5.76)$$

Equation 5.72 with the modified values of B_1 and $\underline{u}$ and equation 5.74 are the equations of state of the open loop position control system in a difference form. They were implemented in a computer programme and results from the programme are considered in Chapter 7.

5.5.3 Input Signal to Wheel Position - Closed Loop

When the system is connected in a closed loop configuration the wheel angle position is sensed by means of a potentiometer attached to the gearbox output shaft. The potentiometer voltage is fed back and compared with the input voltage to form a closed loop position control system. Thus the input signal to the open loop system is now (Vin - δ). Thus remembering that Vin = u_1 and $\delta = x_2$ equation 5.72 becomes

$$x_1 (k + 1) = \psi_1 x_1 (k) + T B_1 [u_1 (k) - x_2 (k)] + T.B_2 u_2 (k) \qquad (5.77)$$

i.e.

$$x_1 (k + 1) = \psi_1 x_1 (k) + \psi_2 x_2 (k) + T B_1 u_1 (k) + T B_2 u_2 (k) \qquad (5.78)$$

$$\text{where } \psi_2 = - T \cdot B_1 = - \frac{T \cdot K_2 \cdot Bm}{J_L \cdot Ra} \qquad (5.78.1)$$

Equations 5.78 and 5.74 are the equations of state of the closed loop position control system in discrete form. They were implemented in a computer programme and the results from the programme are considered in Chapter 7.

5.6 VEHICLE LATERAL RESPONSE - THE MODEL

Equations 5.29, 5.31 and 5.36 give an exact description of the lateral response of the vehicle. It is a highly non-linear description and is not in a form suitable for inclusion in a matrix representation. Furthermore, it is a continuous description and so must be adapted to fit a discrete implementation on the computer. To form a state space description of the system, first the state variables must be chosen. Following Dorf[46] variables are chosen which represent energy storage, and these are seen to be the vehicle attitude ψ and the measured displacement d. This may not be immediately obvious, but if it is realised that it takes energy to set a wheel angle δ, and both these variables represent integrals of δ then their action as energy storage variables is clear. Thus in the state space notation

$$x_3 = \psi \qquad (5.79)$$

$$\text{and} \quad x_4 = d \qquad (5.80)$$

Recalling that $x_2 = \delta$ and rewriting equation 5.31 in a state space form gives

$$\dot{x}_3 = \frac{Vo}{l} \cdot \tan x_2 \qquad (5.81)$$

Replacing the continuous differential $\dot{x}_3$ with the discrete approximation of equation 5.62 gives

$$x_3(k+1) = \psi_5 \tan x_2(k) + x_3(k) \tag{5.82}$$

where $\psi_5 = \dfrac{T \,.\, Vo}{l}$ (5.82.1)

Substituting in equation 5.36 for U and V from equation 5.29 and rewriting in a state space form gives

$$\dot{x}_4 = \frac{Vo \,.\, u}{l} \tan x_2 + Vo.\tan x_3 \tag{5.83}$$

Replacing the continuous differential $\dot{x}_4$ with the discrete approximation gives

$$x_4(k+1) = \psi_6 \tan x_2(k) + \psi_7 \tan x_3(k) + x_4(k) \tag{5.84}$$

where $\psi_6 = \dfrac{T \,.\, Vo \,.\, u}{l}$ (5.84.1)

and $\psi_7 = T \,.\, Vo$ (5.84.2)

Equations 5.82 and 5.84 are the equations of state for the vehicle lateral response.

They are implemented on a digital computer with the next value of x_3 and x_4 being calculated every sample period from the previous values of x_2 x_3 and x_4. The use of a digital computer means that the full form of the expression, including the non-linear tangents, can be implemented and so there is no need to linearise the system. Thus using the state space notation and a computer implementation, a complete analysis can be carried out just as easily as a linear analysis. Results from the programme are considered in Chapter 7.

5.7 LATERAL POSITION SENSOR - THE MODEL

The mathematics developed in Section 5.4 for the lateral position sensor, while accurate, is unnecessarily complex for the purposes of model simulation. Indeed it was never intended as such, but rather was meant to form a basis for developing an understanding of and a specification for the lateral position sensor. This is done later in Section 7.2. For the model a simpler form of sensor characteristic is quite adequate and Figure 5.17 shows a linearised sensor characteristic. Within the single-valued region of the sensor (the sensor window) the sensor output in volts is directly proportional to the distance from the wire, i.e.

$$\text{for } -yo < y < yo \qquad Vs = Ks \cdot y \tag{5.85}$$

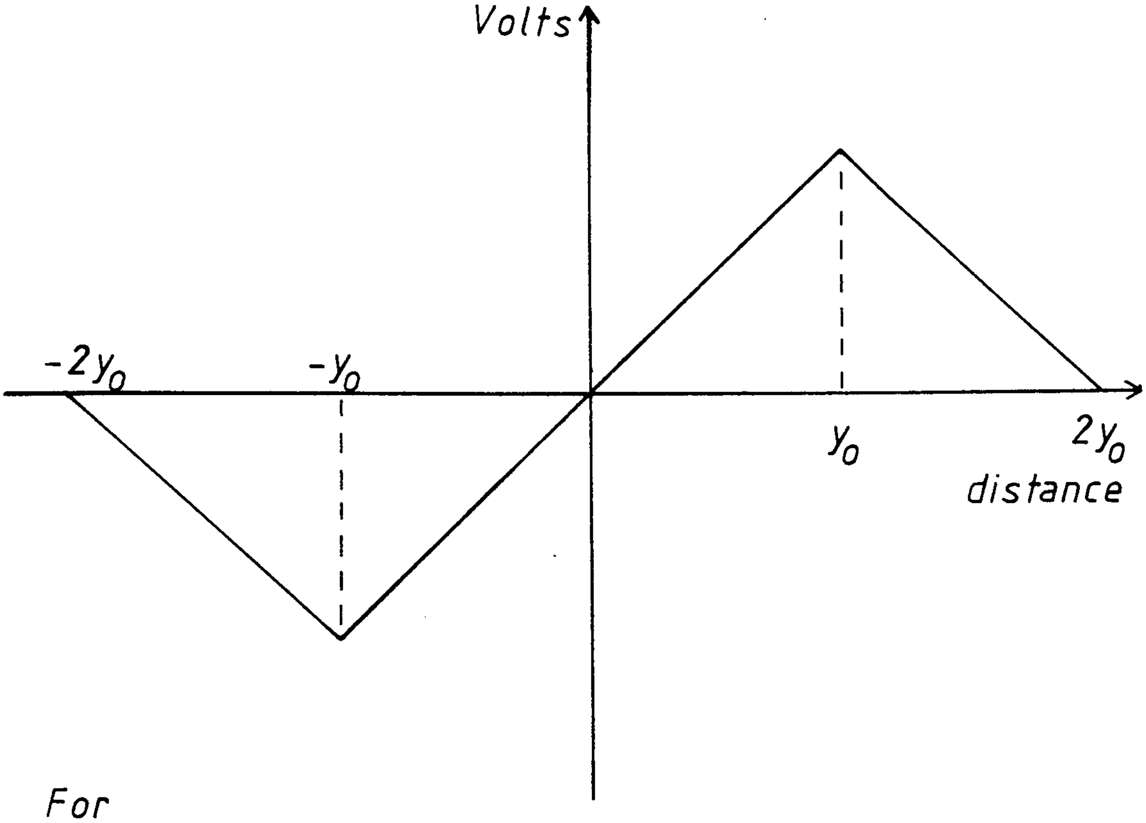
where Vs is the sensor output voltage

y is the distance from the wire

yo is the limit of the sensor window

and Ks is the sensor gain factor

Beyond the edges of the sensor window the linearised characteristic falls off at the same rate as which it grew and thus reaches zero at a distance of 2yo from the wire. For this region,



For $-y_0 < y < y_0$	$V = Ks.y$
For $-2y_0 < y < -y_0$ & $y_0 < y < 2y_0$	$V = Ks.(2y_0 - y)$
For $y < 2y_0$ & $2y < y$	$V = 0$

Figure 5.17 - The Linearized Lateral Position Sensor Characteristic

for $-2yo < y < -yo$

and $yo < y < 2yo$ $Vs = Ks\ (2yo - y)$ (5.86)

Finally, beyond a distance of 2yo the sensor output is zero, i.e.

for $y < -2yo$

and $2yo < y$ $Vs = 0$ (5.87)

This is the form of lateral position sensor characteristic used in all the simulation work.

5.8 SUMMARY

Three major areas of theory have been presented, these being: the steering motor, gearbox and wheels; the vehicle lateral response; and the lateral position sensor. The first two of these are directly applicable to the steering system response whereas the third is more of an aid to sensor selection. From the theory, a discrete form of model has been developed for each section suitable for implementation on a digital computer. Because of the multi-variable nature of the steering system and the fact that it is implemented digitally in a discrete difference equation form, a state space approach has been adopted. This presents an nth order system as a series of n first order differential equations which can then easily be formed into difference equations. The steering system is a fourth order system, and four state variables which represent energy storage elements have been chosen. These are: the speed of the steering motor; the position of the wheels; the vehicle attitude; and the lateral displacement of the lateral position sensor. The four equations of state have been presented, but these are not complete, requiring an extension of the vehicle lateral response theory to cope with wire curvature. This will be delayed until Chapter 7 when the results will be presented and the basic theory validated before extension.

CHAPTER 6

THE VEHICLE AND ITS STEERING CONTROL SYSTEM

6.1 Objectives

6.2 The Test Vehicle

6.3 The Steering Motor

  6.3.1 A Specification for the Steering System

  6.3.2 The Steering Motor

6.4 Motor Control Electronics

6.5 The Sensors

  6.5.1 The Wheel Angle Sensor

  6.5.2 The Lateral Position Sensor

6.6 The Steering System Software

  6.6.1 The Software Philosophy

  6.6.2 The Control Software

  6.6.3 The Input Software

  6.6.4 The Communications Software

6.7 Summary

6.1 OBJECTIVES

The theory and model developed in the previous chapter is applicable to any vehicle with only one steering axis. Thus it is not suitable for the sort of unit load transporter where two wheels in the centre of the vehicle are differentially driven for steering, or for the sort of vehicle where there are two steering axes, thus enabling the vehicle to go sideways. However, within the restriction of a single steering axis fall the majority of industrial battery electric vehicles including fork lift trucks, tow tractors and some types of unit load transporters. To validate the model developed, a steering system was designed and applied to a test vehicle at the sponsoring company. This chapter will give a description of the test vehicle and the control systems used upon it.

6.2 THE TEST VEHICLE

The vehicle upon which the theoretical results were validated and the control systems mounted was a prototype model of the Electruk range of battery powered electric vehicles, manufactured by A. W. D. Electric Vehicles, a division of A. Watson and Dundas Limited. An example of the range of production vehicles is shown in Figure 6.1. The vehicle is intended for use as a rider controlled platform vehicle in which small loads are moved on the platform. If larger loads are to be moved then with the inclusion of an optional towing bracket one or more trailers can be pulled.

The prototype vehicle supplied to Cableform was slightly different from the production version. The vehicle is shown in its original form in

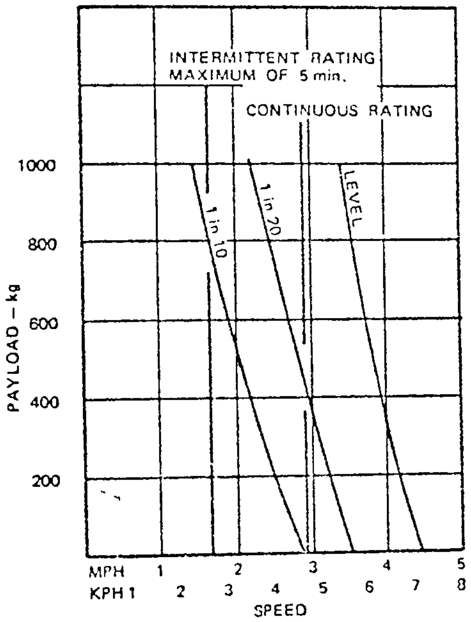
A&D ELECTRUK 1000/18

BASIC CAPACITY

Platform	1000 Kg	2200 lbs

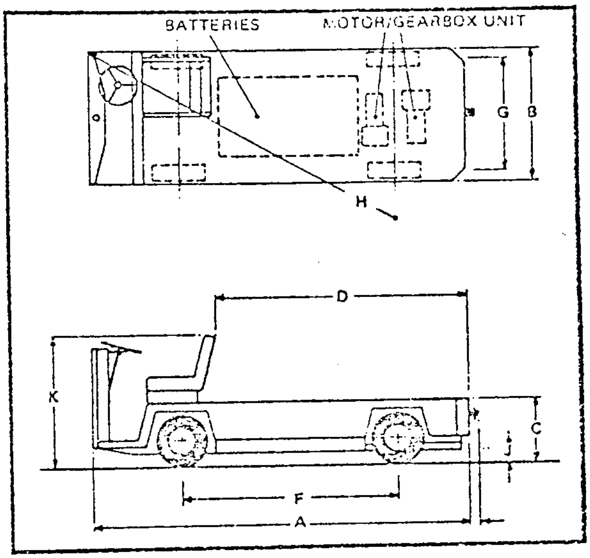
PERFORMANCE

Final Drive Ratio		Speed on Level Ground	
		Laden	Unladen
Standard	1.66:1	3.3 MPH	4.4 MPH
Optional	1.08:1	4.7 MPH	6.7 MPH



DIMENSIONS

		mm	ins.
Length	A	2900	114.2
Width	B	1000	39.4
Platform height	C	460	18.1
Platform length	D	1900	74.8
Two bracket length	E	80	3.1
Wheelbase	F	1645	64.8
Track	G	890	35.0
Turn radius between walls	H	2840	111.8
Ground clearance	J	100	3.9
Height	K	1000	39.4



BATTERIES (48v)

Up to 8.24 Kw. hrs.
Capacity to suit application
Chloride or Oldham traction

STANDARD EQUIPMENT

- Simulated leather steering wheel
- Simulated leather covered upholstered seat
- On/Off key switch
- Battery isolating/charging plug
- On/Off electromagnetic parking brake switch
- Electric horn
- Battery condition indicator
- Direction control lever

TECHNICAL SPECIFICATION

Motors	2 – C.A.V. 0.41 Kw.
Drive	Reduction gearboxes and chains to rear axle
Speed control	Direction control by switch, foot operated throttle and electronic controller
Brakes	7" hydraulic drums on rear wheels foot operated Electro magnetic fail safe disc brakes on motors
Wheels	Pressed steel with 400 x 8 6PR pneumatic tyres
Steering	By worm box
Charging	By separate wall or floor mounted automatic traction charger

OPTIONAL EQUIPMENT

- Different final drive ratios
- Lighting equipment
- Weatherproof Cab (120 Kg) or safety cage
- Passenger seat
- Battrey charger
- plywood platform in lieu of chequer plate
- Towing bracket
- Cushion tyres
- Spare wheel

A&D ELECTRIC VEHICLES
HILLINGTON ROAD, GLASGOW
Southern Office: 12 Coombe Court, Thatcham, Berkshire.

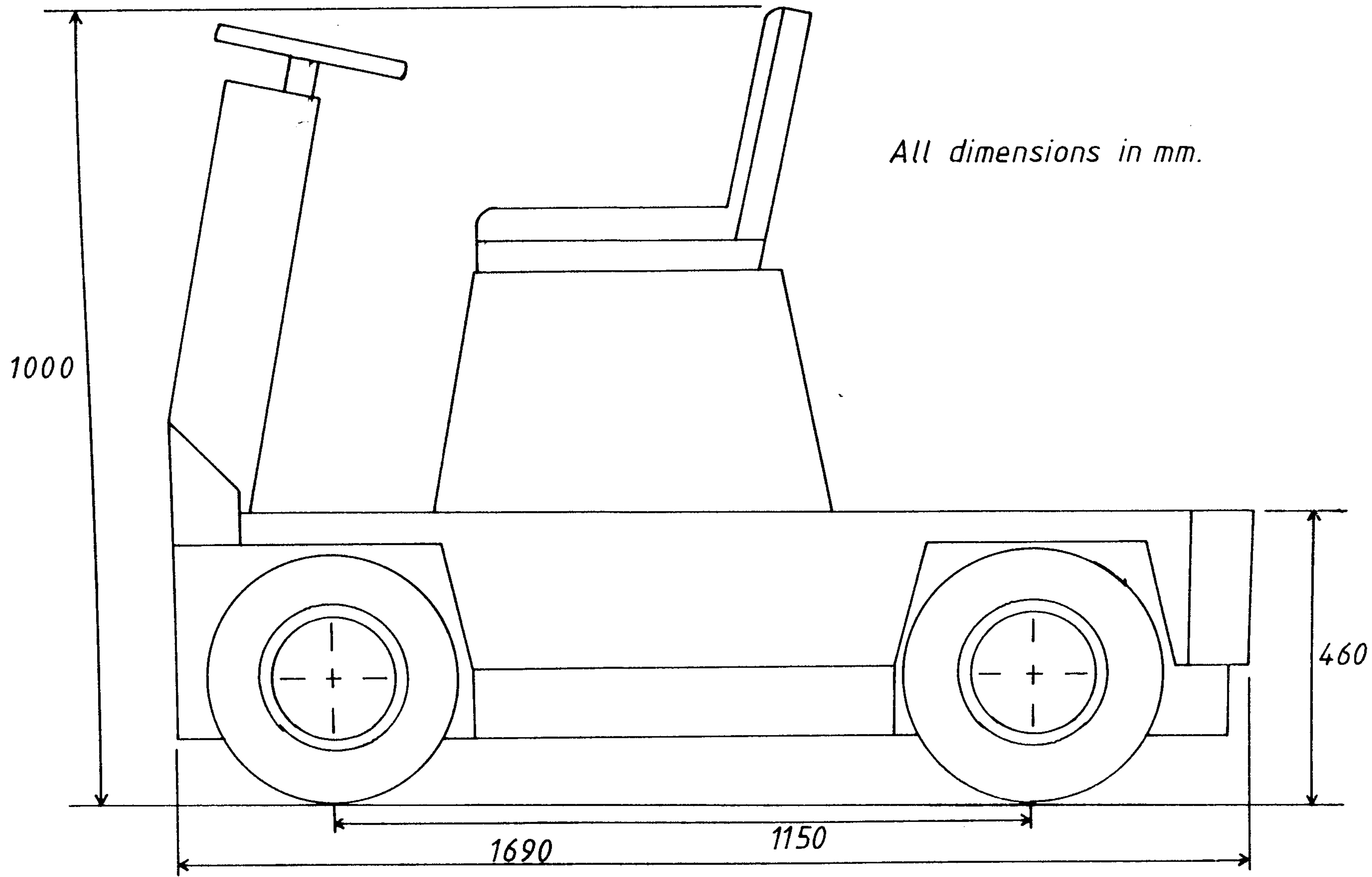
Telephone: 041 - 882 7111
Telex: 778370
Telephone: (0635) 62074

Figure 6.1 - The Electruk Vehicle Production Range

Figure 6.2. It is 1.69 metres long with a wheelbase of 1.15 metres. The vehicle width is 0.92 metres and the height of the seat and steering column is 1 metre. The platform height is 0.46 metres. The vehicle weighs 550 kg. The vehicle had a tall battery pack and the seat was mounted over the batteries on a cover which pivoted backwards to give access to the battery compartment. There is no towing bracket.

An extra cog was fitted to the steering column to enable a motor to be connected via a chain drive to the steering gear and extra sprockets were fitted to the rear axle to provide a final drive ratio of 2.53:1 giving an unladen top speed on level ground of 1.3 ms^{-1} (2.9 mph). There were two CAV 0.41 Kw series motors for traction, one driving each rear wheel through a reduction gearbox and chain to the split rear axle. The vehicle was supplied with hydraulic brakes operated by a foot pedal and each motor has an electromagnetic brake fitted to it. There was also a foot accelerator pedal supplied, but this was left unconnected since no controllers were supplied with the vehicle. The traction motors were rewound as separately excited motors and controllers suitable to allow the vehicle to be driven both forwards and backwards were installed.

There have been four major variants of the steering system using two different steering motors and hence involving two different mechanical systems. The mechanical design of the first system is shown in Figure 6.3. The wheels are pivoted about the points 1 and 2, and are made to turn by the movement of the track rods 3 and 4. The track rods are connected at one end to a point in front of the wheel pivot points, 5 and 6, and at the other end to an eccentrically mounted bolt 7 on a gearwheel 8. This gearwheel is driven through a chain drive 9 by another gearwheel 10 which is attached to the bottom of the steering column 11. The



All dimensions in mm.

Figure 6.2 - The Test Vehicle, Original Shape

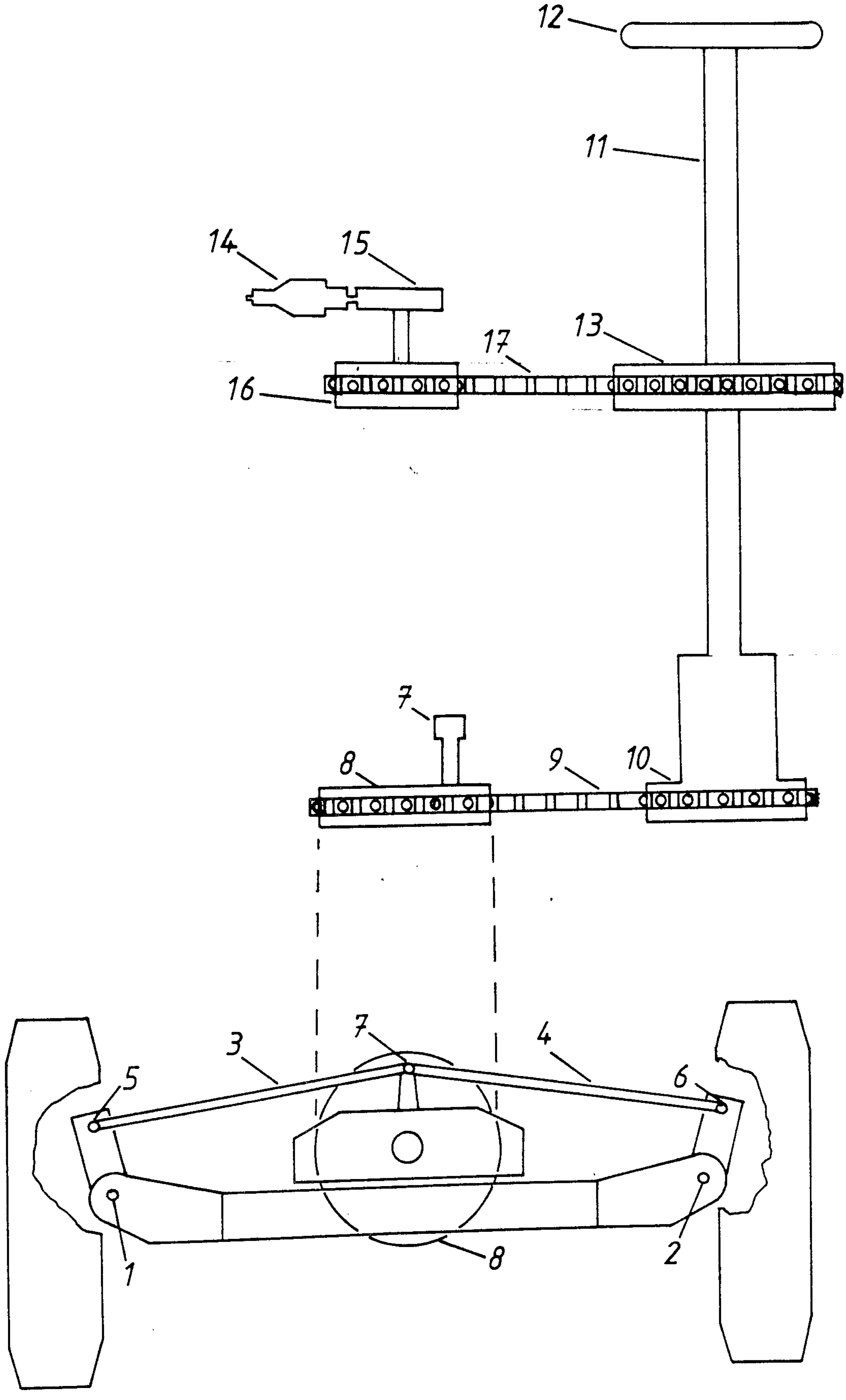


Figure 6.3 - The Steering Geometry

steering column is normally made to rotate by manually turning the steering wheel 12. The provision of the extra cog 13 fitted to the steering column enables the steering motor 14 to turn the steering column and hence the wheels through a gearbox 15 and a gearwheel 16, attached to the extra cog through a chain drive 17.

The first steering motor which was used with this system was a d.c. series motor. It was only a small motor in terms of power and so a large gear ratio was required to present an adequate torque at the steering wheels. The gear ratio used was 800:1 built up of a 100:1 ratio in gearbox 15; a 2:1 ratio between gearwheels 16 and 13; and a 4:1 ratio between gearwheels 10 and 8. Motor torque is required primarily to overcome the static friction in the system, which is considerable. This "stiction" torque is needed to begin to rotate the wheels about the points 1 and 2 against the friction between the tyre contact patch and the ground. The stiction torque was measured mechanically at the steering column and found to be 24 Nm which represents 96 Nm at the steering wheels. It was also measured by recording the peak current required in the motor to start to turn the wheels. A current of 8.7A was recorded with the series motor and this represents a torque of approximately 12 Nm in the gearbox output. This represents 96 Nm at the steering wheels.

The steady state current in the series motor when turning the steering gear was measured at 6.5A. This represents a torque of 7 Nm which reflects to 56 Nm at the steering wheels. At this torque value, the motor could not turn swiftly enough to give the steering system the necessary speed of response and so a larger motor was necessary.

The next motor fitted was a NECO 370W, separately excited, 24V d.c. geared motor unit with a gearing ratio of 45.6:1. The motor can be seen in Figure 6.6. To install the new motor the mechanical fixtures had to be redesigned and at the same time as this was done, the vehicle itself was redesigned to provide two powered roller platforms for the first stage of the load handling project. The mechanical design for both motor fixture and roller platforms was provided by Mr P T Willes and is reproduced here with his kind permission. The new shape of the vehicle can be seen in Figure 6.4 and plate 1 where the new motor can also be seen quite clearly in its new position. With reference to Figure 6.3, the output of the gearbox is connected directly to gearwheel 8, driving the wheels directly. Thus the only gearing in the system is the 45.6:1 ratio of the gearbox and this enables a much swifter speed of response to be obtained. Referring to Figure 6.4 the vehicle shape has been maintained in all dimensions except the vertical. Here the loss of the steering column, made possible by the direct coupling of the motor to gearwheel 8 and the use of low profile traction batteries enables the vehicle to achieve a height, even with the roller platforms, of only 0.6 m. This gives the vehicle a shape closer resembling that of commercial unit load transporters (plates 4 and 5). This is the present shape of the test vehicle and in this form it provides a test bed for all the control systems of project one.

6.3 THE STEERING MOTOR

6.3.1 A Specification for the Steering System

The specification for the steering system is determined by the operational requirements of the steering system and the nature of the load

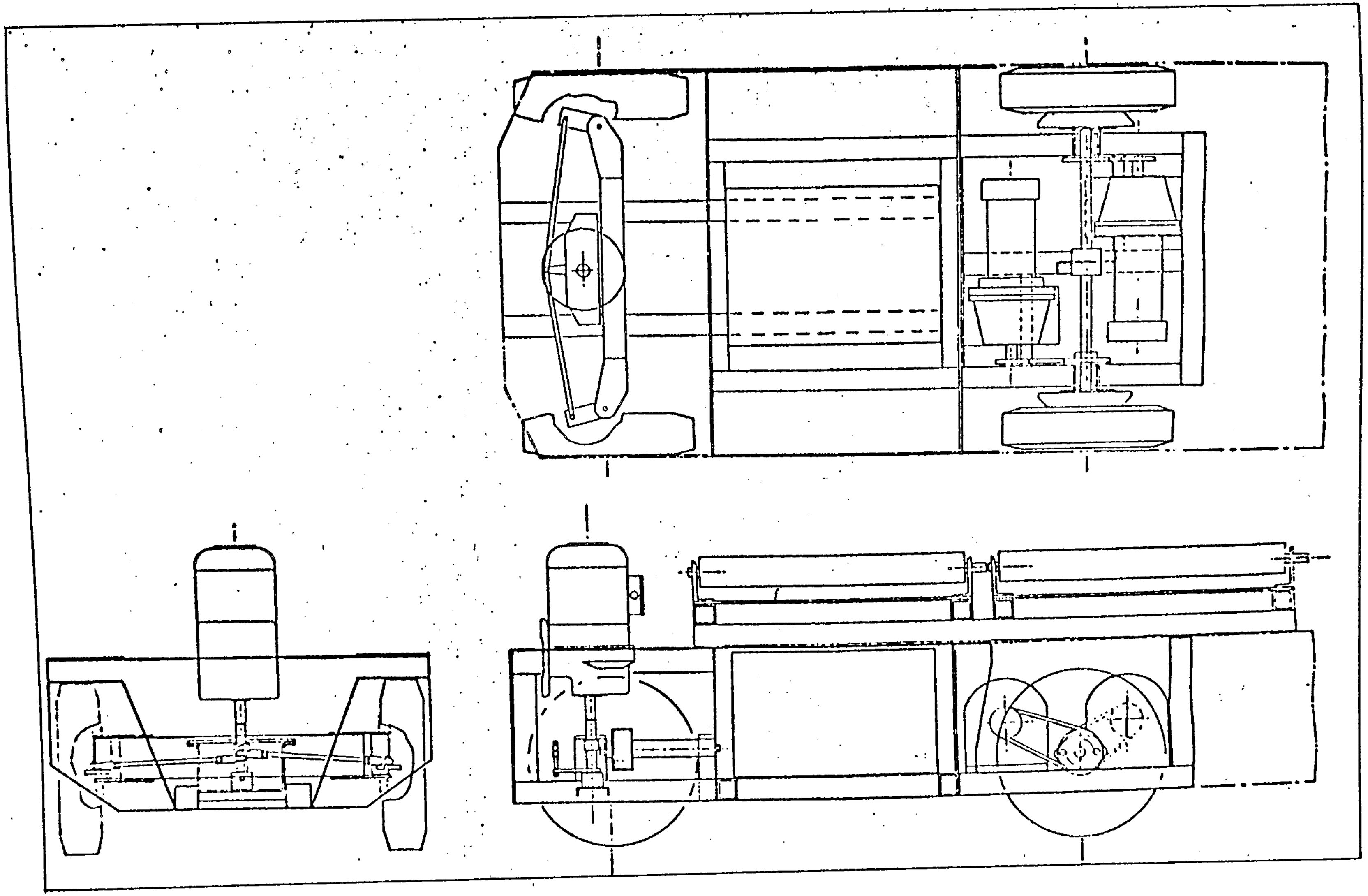


Figure 6.4 - The Test Vehicle - Modified Shape

on the motor. The operational requirement is for as swift a speed of response as possible without excessive ringing or oscillation about the set position. Furthermore the system must maintain the set angle despite external disturbances such as an oil patch reducing friction or a knock to the wheels from an uneven surface. These requirements lead to the use of a closed loop position demand system in which feedback of the wheel position minimises the effect of external disturbances and the use of a high open loop gain can give the system a swift speed of response with enough damping to minimise the oscillations. The nature of the load is one of high friction and low inertia. The turning of the wheels about a vertical axis entails the scrubbing of the rubber tyres across a concrete floor. There is a high coefficient of friction between the rubber and the floor (luckily for traction) and so even at higher speeds of turn the wheels present a considerable friction to the motor. However, the wheels and the steering gear are not in themselves particularly massive and after reflection through the gear ratio, the inertia they present to the motor is low. Thus it is the armature and gearbox inertia which dominates the total inertia of the steering system.

Placing a motor in a closed loop position control system results in a second order, type zero system (see Section[46] 5.2). The settling time of such a system to a step demand is given by

$$Ts = \text{Settling time} = \frac{4}{\zeta\, Wn} \tag{6.1}$$

Substituting for ζ and Wn from equations 5.19 and 5.20 gives

$$Ts = \frac{8}{a} \tag{6.2}$$

$$\text{where } a = \frac{1}{T_1} = \frac{Bm^2}{Ra\ J} \qquad (6.3)$$

For Ts to be as small as possible requires as large a value of a as possible. In effect this demands a large bandwidth from the motor where the bandwidth is the width of the plateau portion of the Bode plot in Figure 5.3. For a to be large, Bm must be large and Ra and J must be small. The smaller Ra the armature resistance is, the more current can flow into the motor for a given applied voltage and the larger Bm the motor constant is the more torque this current represents. J is the armature inertia and the lower this is, the quicker a given torque can accelerate the motor. Thus the condition of a large value of a demands a high torque, low inertia motor. Such a motor can accelerate and decelerate rapidly and so quickly change its angular position. The best examples of such a motor are the permanent magnet d.c. servo motors which are designed specifically as high torque, low inertia motors. The main problem with them is their length. Because of the high running torque (≅ 50 Nm) and even higher stiction torque (≅ 100 Nm) of the steering system, even the largest motor must operate through a gearbox. To keep the polar moment of inertia low, the motors have a long, cylindrical construction and with an in-line gearbox fitted as well, the resulting unit is somewhat long. Although theoretically ideal, such a motor has not unfortunately been available for use on the project.

6.3.2 The Steering Motor

The first steering motor used was a CAV type GM1A 24v d.c. series motor, which was made available at the start of the project. The main reason that this motor was inadequate is due to the series form of the speed-torque curve (see Figure 6.5). For a series motor, high torque is available only at low speeds. Thus in a high friction situation, such as the vehicle steering system, the necessary torque can only be supplied at low speeds and the motor could not react quickly enough. Thus a new motor was made available. This was a NECO type DS5A d.c. motor with an in-line gearbox. Originally wound as a shunt motor, it was rewound as a separately excited motor and the armature series turns were taken out. The armature series turns were taken out to prevent faulty operation of the motor during rapid switchover of direction. The motor can be seen quite clearly in position vertically at the front of the vehicle in Figure 6.4 and plate 1. Drawings of the type 5A motor and the type DS gearbox can be found in Figures 6.6 and 6.7 respectively. The curve which characterises a separately excited motor is the plot of power in the field versus the motor constant (Pf vs. Bm) and this is shown in Figure 6.8. For the swiftest operation Bm must be as large as possible and this demands the maximum power in the field. The rated output torque of the gearbox is 80 lb ft. and although this is only twice the stall torque of the CAV motor, the NECO motor is a considerably more powerful motor since this same torque is available even at high speeds. This flat form of speed-torque response is characteristic of separately excited and permanent magnet motors and is ideally suited to low inertia, high friction loads such as the vehicle steering system. A graph showing the different forms of the speed-torque response for series and separately excited motors is shown in Figure 6.5.

The NECO motor has proved adequate as a steering motor for operation of the vehicle steering only at relatively low vehicle speeds (≤ 0.5 ms^{-1}). The main disadvantage of the motor is its large mechanical time constant of 260 ms. This compares with servomotor time constants of

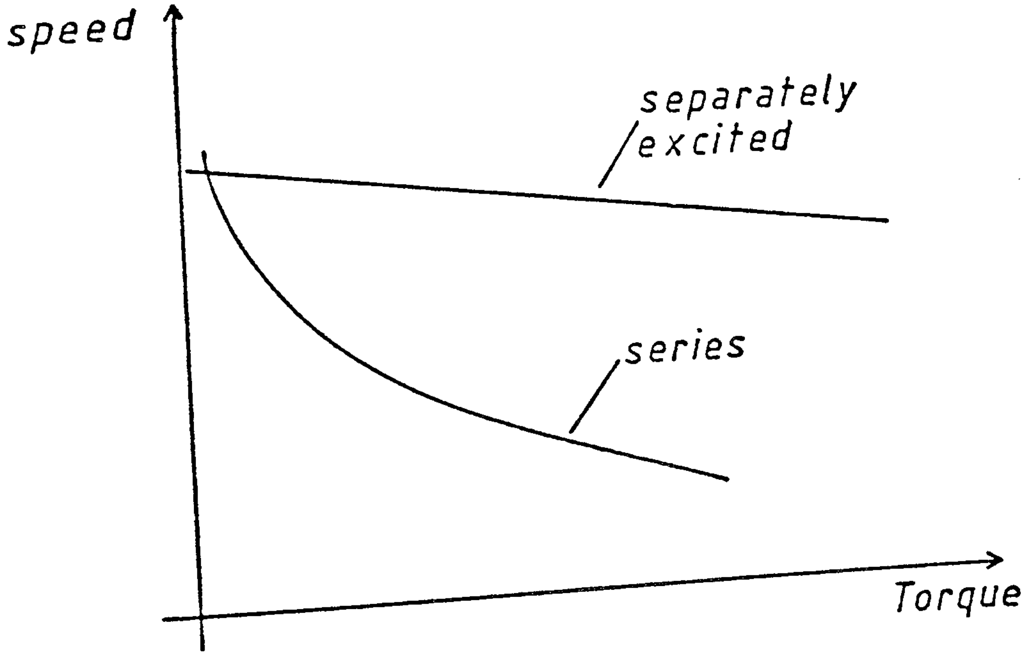
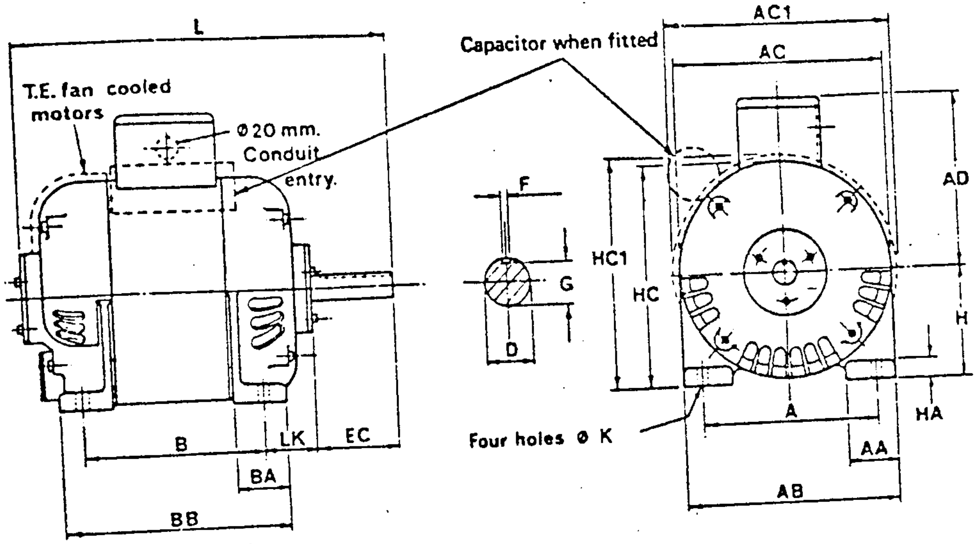


Figure 6.5 - The Speed vs. Torque Profile for Series & Separately Excited Motors

FRAME 5, 5A, 5B DIMENSIONS

DRIP PROOF, TOTALLY ENCLOSED OR TOTALLY ENCLOSED FAN COOLED MOTORS FOOT MOUNTED



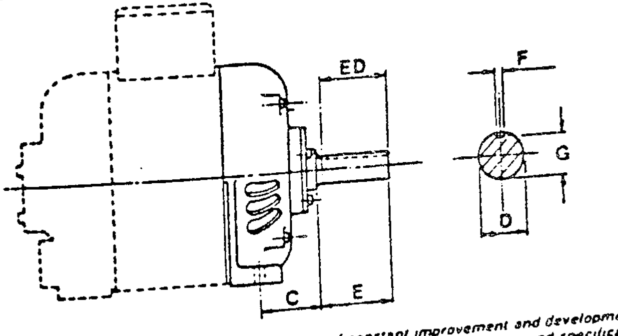
Frame Number		A	B	AA	BA	AB	BB	AC	AC1	AD	EC	H	HA	HC	HC1	K	L	LK
5	mm	149.2	130.2	38.1	31.8	174.6	158.7	174.6	130.5	128.6	66.7	88.9	9.53	176.2	184.2	9.53	279.4	41.3
	ins	5 7/8	5 1/8	1 1/2	1 1/4	6 7/8	6 1/4	6 7/8	7 1/2	5 1/16	2 5/8	3 1/2	3/8	6 15/16	7 1/4	3/8	11	1 5/8
5A	mm	149.2	149.2	38.1	31.8	174.6	177.8	174.6	190.5	123.6	66.7	88.9	9.53	176.2	184.2	9.53	298.5	41.3
	ins	5 7/8	5 7/8	1 1/2	1 1/4	6 7/8	7	6 7/8	7 1/2	5 1/16	2 5/8	3 1/2	3/8	6 15/16	7 1/4	3/8	11 3/4	1 5/8
5B	mm	149.2	181.0	38.1	31.8	174.6	209.5	174.6	190.5	128.6	66.7	88.9	9.53	176.2	184.2	9.53	330.2	41.3
	ins	5 7/8	7 1/8	1 1/2	1 1/4	6 7/8	8 1/4	6 7/8	7 1/2	5 1/16	2 5/8	3 1/2	3/8	6 15/16	7 1/4	3/8	13	1 5/8

SHAFT AND KEYWAY

Frame Number		Under 1 HP			1 HP		
		D	F	G	D	F	G
5 5A 5B	mm	15.875 15.862	–	–	15.875 15.862	4.775 4.750	13.145 13.005
	ins	0.5250 0.6245	–	–	0.6250 0.6245	0.188 0.187	0.5175 0.5120

KEYWAY ON MOTOR UNDER 1 HP MUST BE REQUESTED ON ORDER.

STANDARD METRIC SHAFT AND KEYWAY



C	50
D	16.008 15.997
E	40
ED min.	25
F	5.00 4.97
G	13.0 12.9

NECO Order Ref.
for Standard
Metric Shaft-
frames
5, 5A, 5B
ME 12225

IT IS IMPERATIVE WHEN ORDERING MOTOR WITH METRIC SHAFT THAT THE METRIC REFERENCE IS GIVEN:

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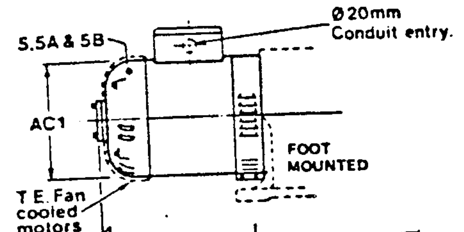
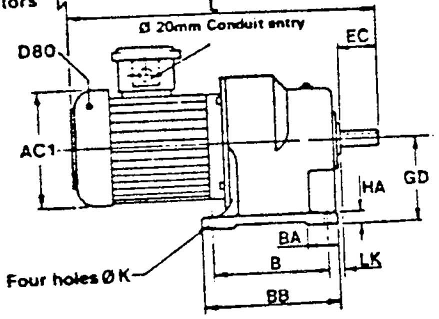
Figure 6.6 - The NECO Type 5A D.C. Motor

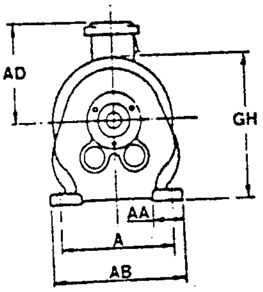
GEARED MOTOR UNITS
COAXIAL TYPE DS DIMENSIONS

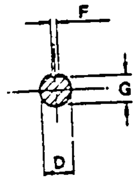
FOOT MOUNTED see overleaf for flange mounted.



<table>
<tr><th rowspan="3">Frame</th><th colspan="6">DIMENSIONS</th><th rowspan="3">Nett Weight kg</th></tr>
<tr><th colspan="2">AC1</th><th colspan="2">AD</th><th colspan="2">L</th></tr>
<tr><th>mm</th><th>ins</th><th>mm</th><th>ins</th><th>mm</th><th>ins</th></tr>
<tr><td>5</td><td>190.5</td><td>7½</td><td>128.6</td><td>5¹⁄₁₆</td><td>412.8</td><td>16¼</td><td>25</td></tr>
<tr><td>5A</td><td>190.5</td><td>7½</td><td>128.6</td><td>5¹⁄₁₆</td><td>425.5</td><td>16¾</td><td>28</td></tr>
<tr><td>5B</td><td>190.5</td><td>7½</td><td>128.6</td><td>5¹⁄₁₆</td><td>463.6</td><td>18¼</td><td>33</td></tr>
<tr><td>D80</td><td>156</td><td>-</td><td>123</td><td>–</td><td>450.9</td><td>17¾</td><td>25</td></tr>
</table>





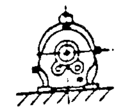
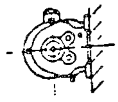
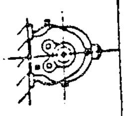
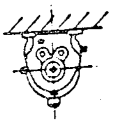
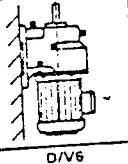
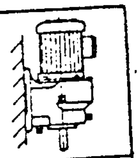


	A	B	AA	BA	AB	BB	EC	GD	GH	HA	K	LK
mm	161.9	161.9	44.5	44.5	190.5	190.5	57.2	114.3	201.6	15.9	12.7	20.6
ins	6⅜	6⅜	1¾	1¾	7½	7½	2¼	4½	7¹⁵⁄₁₆	⅝	½	¹³⁄₁₆

SHAFT AND KEYWAY

	D	F	G
mm	22.225 22.212	6.350 6.325	18.606 18.466
ins	0.8750 0.8745	0.250 0.249	0.7325 0.7270

SEE PAGE 131 FOR ALTERNATIVE METRIC SHAFTS

MOUNTING						
NECO/B.S.	Floor/B3	A/B7	B/B5	E/B8	D/V6	C/V5
IEC MTG	IM 1001	IM 1051	IM 1051	IM 1071	IM 1031	IM 1011
*Oil Quantity Max. Universal Mounting	1.7 pints	2 pints	2 pints	2.8 pints	3.8 pints	3 pints

*See pages 129 and 130 for recommended lubricants

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Figure 6.7 - The NECO Type DS in-line Gearbox

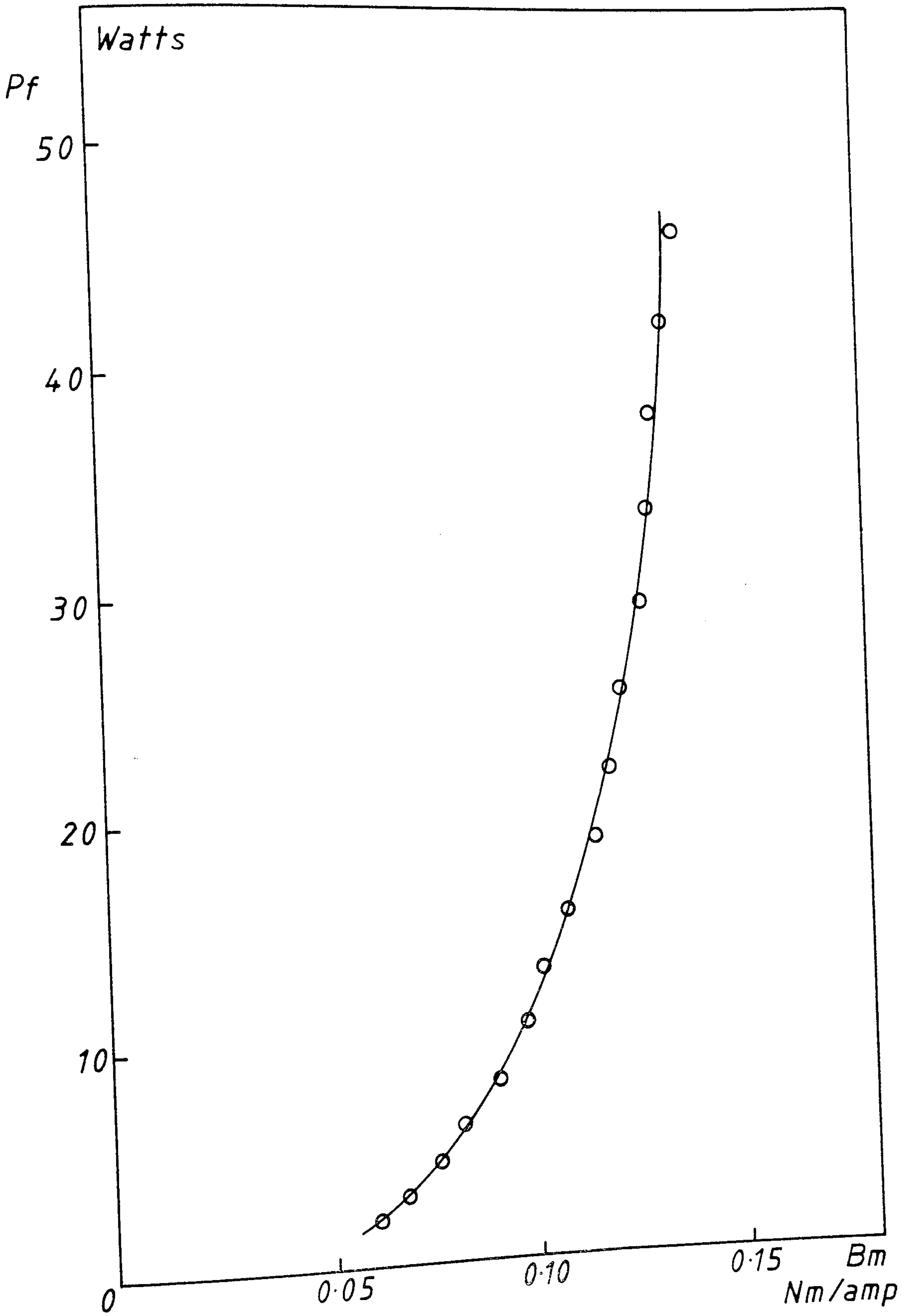


Figure 6.8 - The NECO Motor
The Pf vs. Bm Curve

typically 20 ms, and as low as 12.7 ms for permanent magnet motors and 7.3 ms for rare earth magnet motors. This is due to the large moment of inertia of the NECO motor armature. Servomotors are designed to minimise this polar moment of inertia. The effect of the large motor time constant is to limit the speed of response of the steering system and hence limit the speed at which the vehicle can negotiate a curve of given radius.

Although both motors were readily available to the project, neither is particularly suitable as a steering motor. The series motor has the wrong shape of speed-torque response and the separately excited motor has too high a moment of inertia for its armature. However, both motors have acted to show what sort of motor is required and have been suitable test beds on which to validate the theoretical work.

6.4 MOTOR CONTROL ELECTRONICS

The purpose of the motor control electronics is to take the control signal from the microprocessor and process it into a form suitable for driving the motor. The control signal out of the microprocessor consists of a digital word whose value indicates the mark-space ratio required on the motor. This digital word needs to be turned into a pulse train with the required mark-space ratio and this pulse train then needs to be amplified to a level suitable for driving the motor. Thus two major components can be identified. The first unit is the control unit which turns the digital word into a pulse train of the required mark-space ratio. The method chosen to do this was to maintain a fixed frequency of pulse repetition and to vary the width of the pulse according to the digital word. Thus the unit is a pulse width modulator (PWM). The reason this method was chosen is that simple electronics external to the processor can be used to generate the duty cycle and so no processor time is lost in timing cycles or duty cycle generation. The second unit is the power unit which provides the buffer between the TTL level logic of the pulse width modulator and the high currents needed to drive the motor.

The NECO shunt motor was initially controlled by applying proportional control to the armature and switching the field to allow for a change in direction. However, because of the high value of field inductance, something like 500 ms was required for the field to decay in one direction and build up in the other. This limits the reponse speed of the steering system and hence of the vehicle. Tests in which the field was varied (see Section 7.3) showed that it was best to maintain full field, and so the ability to alter the field was not required. The lower value of armature inductance means that a given current in the armature can be switched much faster than the same current in the field. Furthermore, since there are no step changes in the guidance track, a change in direction will occur at low values of armature current. Thus an armature switched controller can respond to a change in direction much faster than a field switched controller. Also such a controller is suitable for servomotors.

The power unit circuit diagram is given in Figure 6.9. It is a standard unipolar drive "H" type PWM amplifier[56]. The control unit is shown in two parts. Figure 6.10 shows the logic control of the circuit. This provides all the functions of supplying the PWM signal to the correct output according to the direction signal. It also provides the interlock feature. This interlock operates just after a change in direction. It delays the turning on of the transistors to rotate the motor in its new

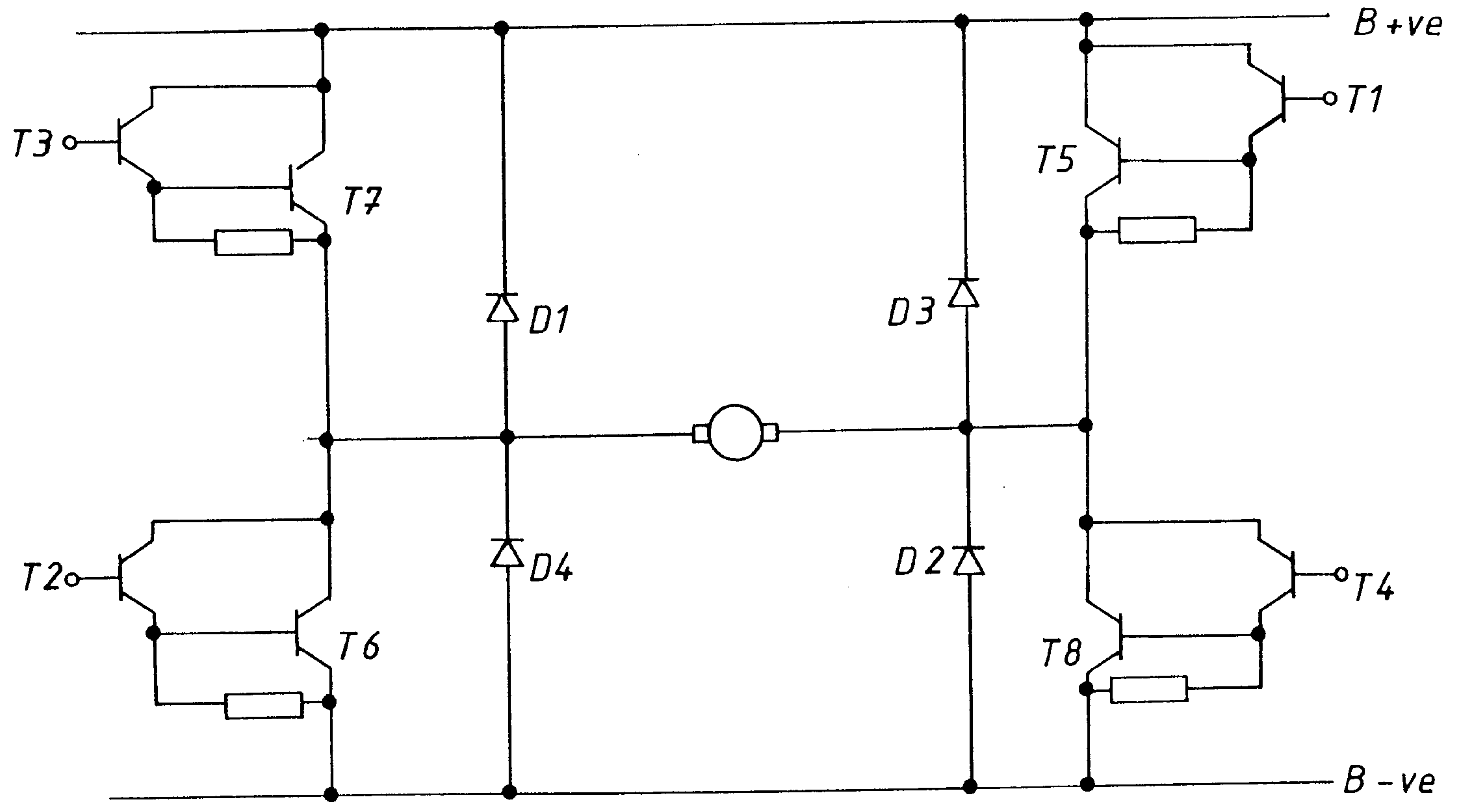


Figure 6. 9 -The Separately Excited Motor Controller with Armature Switching
The Power Circuit

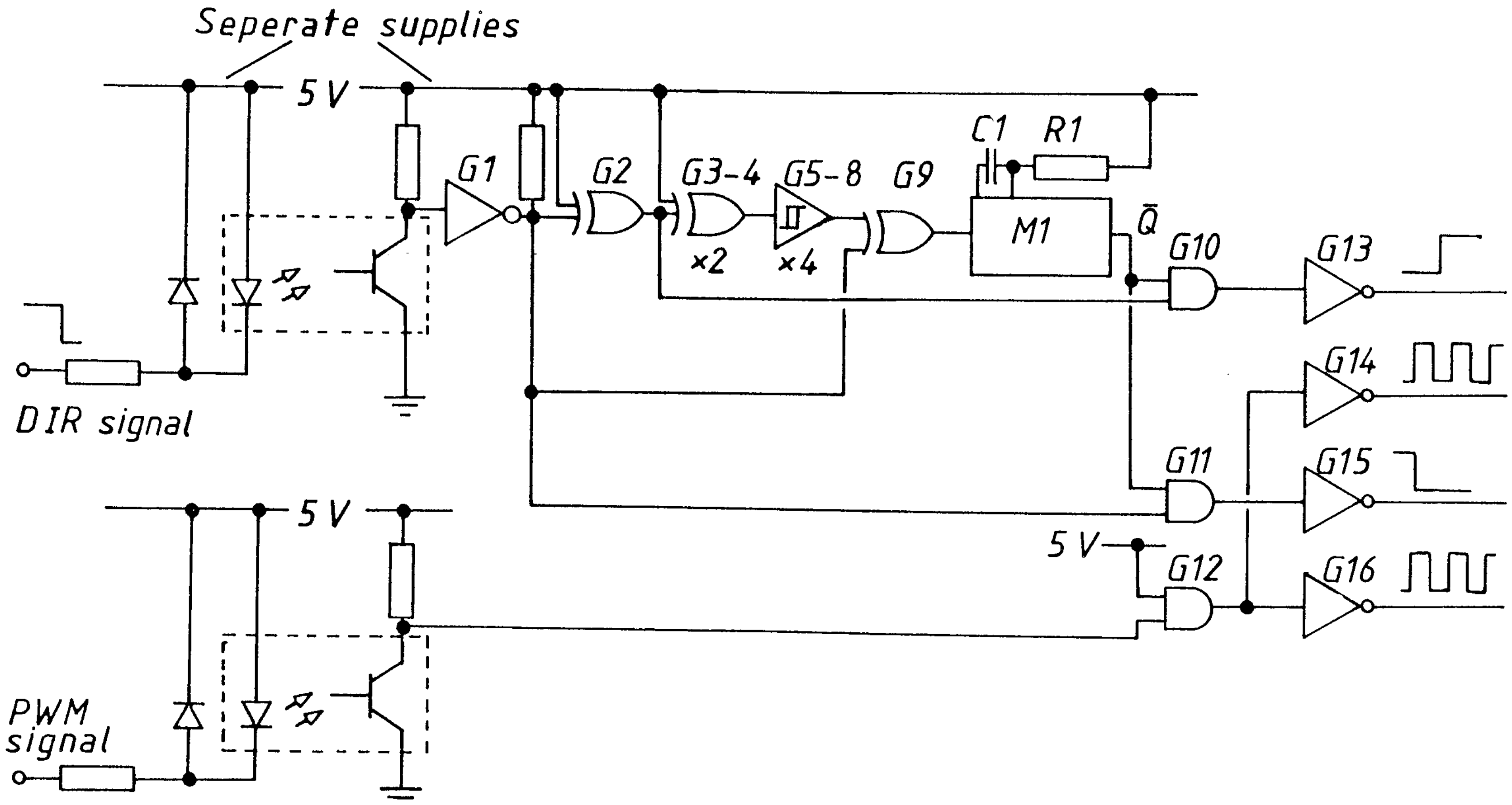


Figure 6.10-The Separately Excited Motor Controller with Armature Switching
The Control Unit Logic

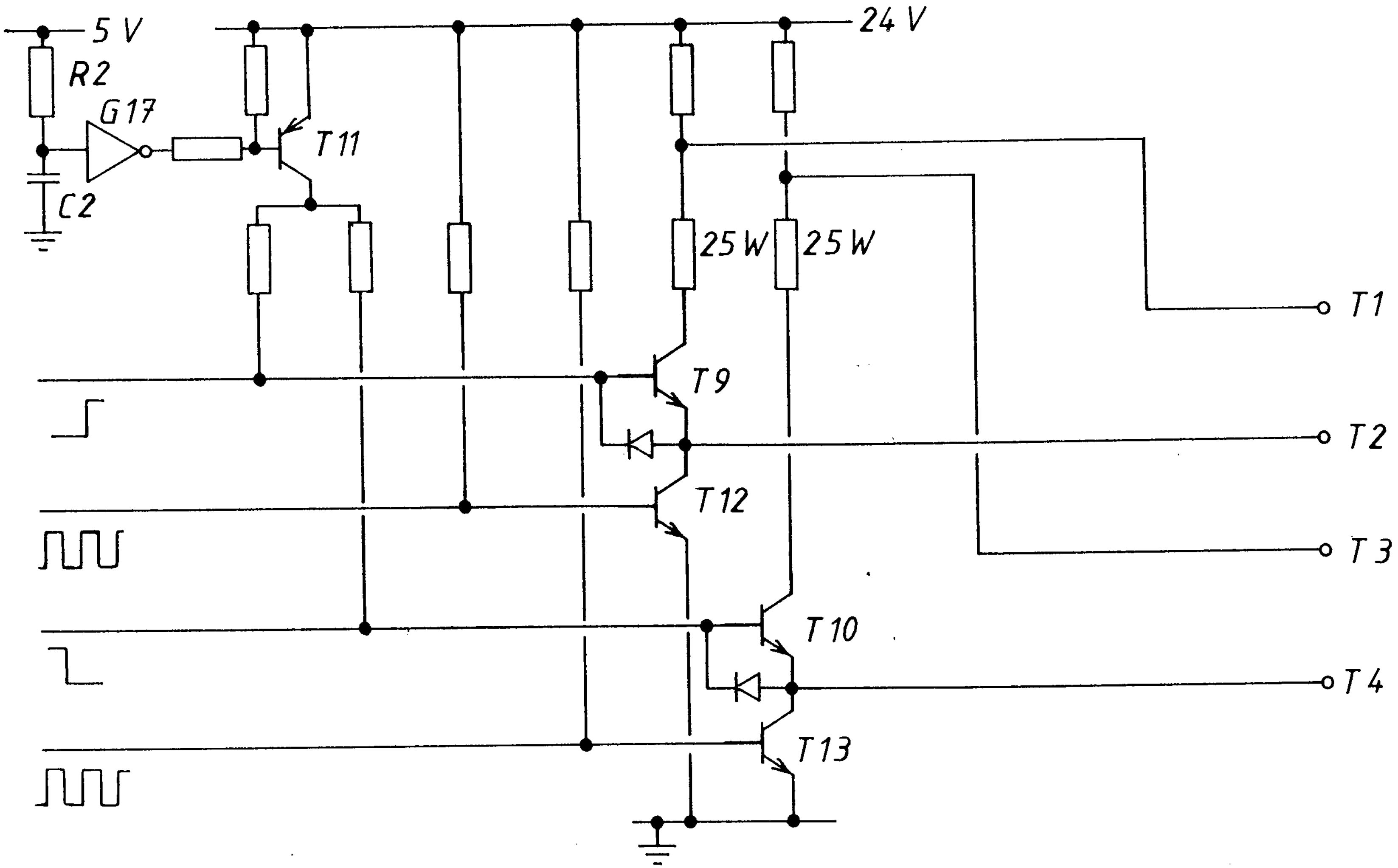


Figure 6.11 - The Separately Excited Motor Controller with Armature Switching
The Control Unit Power Interface

direction for a time sufficient to allow the transistors which had previously been pulsing to turn off. This prevents both arms of the "H" type power unit from being turned on at the same time and so avoids short circuiting the battery. Figure 6.11 shows the interface between the control logic and the power unit. It simply amplifies the PWM and direction signals from the logic board to levels suitable for driving the power unit.

These three circuits together provide the control for a separately excited, armature controlled, d.c. motor. The circuits are original designs due to Mr C Watson and Mr R H Tilbury and are reproduced here with their kind permission.

6.5 THE SENSORS

The steering system as developed uses two sensors. One measures the wheel angle and the other measures the lateral displacement of the track from the vehicle centre line. The sensors described here are those developed for vehicle project one. The wheel angle sensor is a potentiometer. The lateral displacement sensor is the wire guidance sensor. Its theoretical background has been given in Section 5.4 and this section will merely give some of the physical details of the sensor.

6.5.1 The Wheel Angle Sensor

The sensor used to measure wheel angle is a 1 K Ω potentiometer. The wiper is attached to gearwheel 8 of the steering system (see Figure 6.3), and the case is connected to a bracket bolted to the vehicle chassis. Thus the wiper rotates as gearwheel 8 turns. The potentiometer has 5 volts put across the windings which have a field of turn of 270 degrees. Thus the wiper gives an electrical output whose d.c. value represents the angle at which the wheels are set. Figure 6.12 shows the calibration of the potentiometer which gives a linear variation of output voltage against input shaft angle. The slope is 1 volt per radian.

The potentiometer output is fed into the analogue-to-digital converter where a change of 20 mV can be detected. This is equivalent to an angle of 0.02 radians which is thus the resolution of the wheel angle sensor. For an angle of 0.02 radians on the steering wheels the front of the vehicle as represented by the point u = 1.4 moves a lateral displacement of 30 millimetres for 1 metre of forward travel. This represents an error of 3%. Greater accuracy could be achieved by putting a larger supply voltage across the potentiometer, or by using a potentiometer with a smaller field of turn, but it is doubtful if this would lead to greater positional accuracy of the wheels since this is dominated more by the friction between the tyres and the ground than the resolution of the sensor. The potentiometer provides a linear sensor characteristic, and due to its simplicity has proved to be rugged and stable in operation.

6.5.2 The Lateral Position Sensor

The lateral position sensor takes the form of two coils which measure the distance from a guide wire carrying an alternating current of a few kilohertz. This guide wire forms the track that the vehicle is required

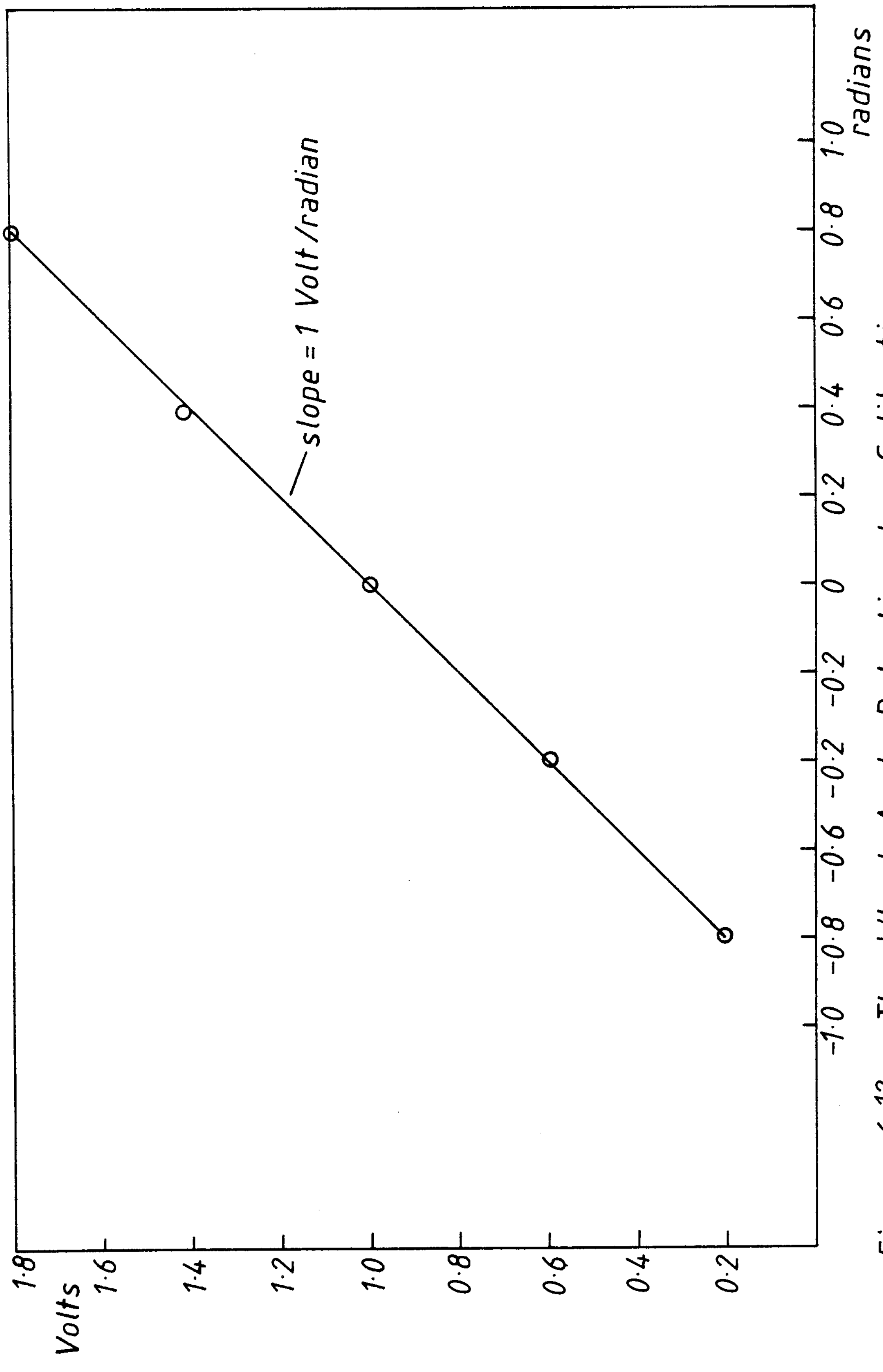


Figure 6.12 - The Wheel Angle Potentiometer Calibration

to follow. The theoretical background has been given in Section 5.4 and the topic of coil design will be dealt with in more depth in Section 7.2. Here it is sufficient to note the form of the sensor used, and the practical details relevant to using the sensor.

A coil can be represented by an inductance and a resistance in series (see Figure 6.13). To provide both a larger output from the coil and also greater noise immunity to the sensor, the coils were both tuned. The electrical representation of a tuned coil is shown in Figure 6.13.

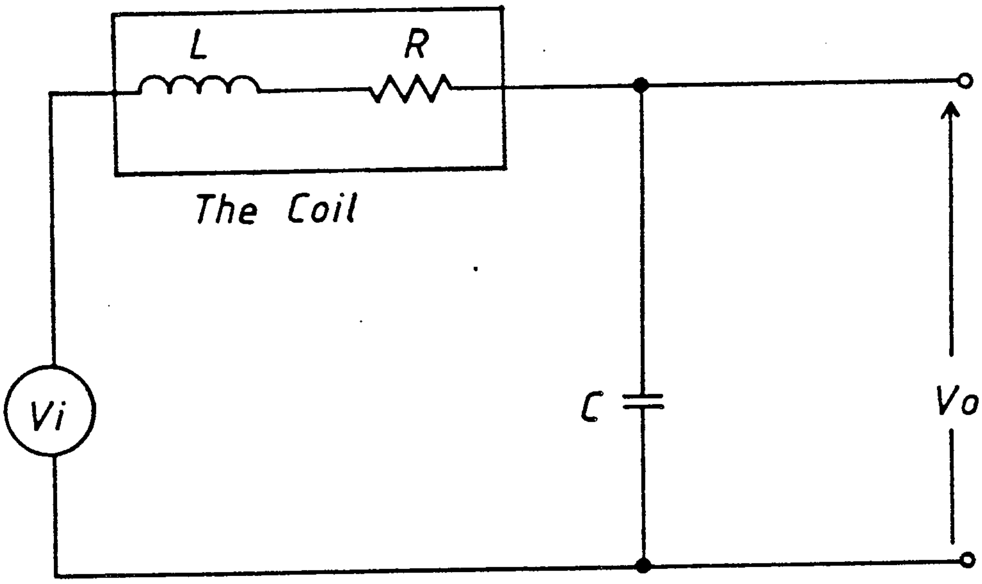


Figure 6.13 - Electrical Representation of a Tuned Coil with a Voltage induced in it

The circuit transfer function is given by [53]

$$\frac{Vo}{Vi} = \frac{1}{1 + j\,w\,C\,R - w^2\,LC} \qquad (6.4)$$

where Vo is the amplitude of the circuit output signal

Vi is the amplitude of the circuit input signal

w is the frequency of the input signal

L is the circuit inductance

R is the circuit resistance

and C is the circuit capacitance

Practically, Vi represents the voltage induced in the coil, Vo represents the output voltage from the tuned coil circuit, L and R are the coil parameters and C is the tuning capacitor. The circuit resonates when

$$4 \pi^2 fo^2 LC = 1 \qquad (6.5)$$

where fo is the resonant frequency

$$\text{i.e. } fo = \frac{1}{2 \pi \sqrt{LC}} \qquad (6.6)$$

The coil inductances are nominally 200 millihenries and so a capacitance of 0.1 microfarads was chosen to give a resonant frequency close to 1 kilohertz. The circuit resistance determines the Q-value of the tuned coil. A low value of R gives a high Q-value. This means that there is a sharp peak in the coil output at resonance (see Figure 6.14). Although this gives larger values of output when the circuit is in resonance it means that the tuned coil is rather sensitive to variations in line frequencies. It also means that small variations in coil parameters and the value of the tuning capacitor, have a major effect on the tuned coil output. To avoid this unnecessary sensitivity, a series resistance is added to the

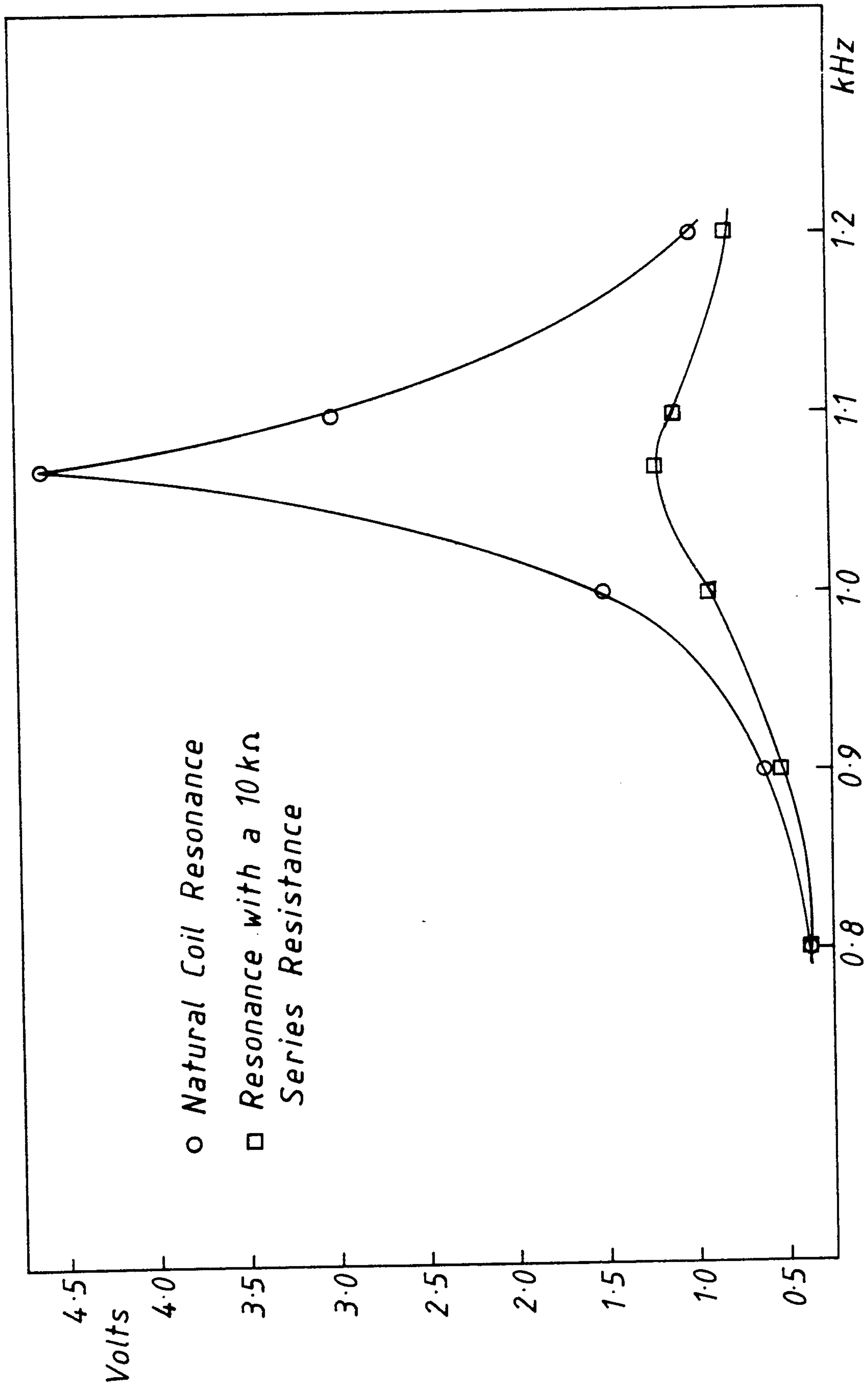


Figure 6.14 - Tuned Coil Resonances

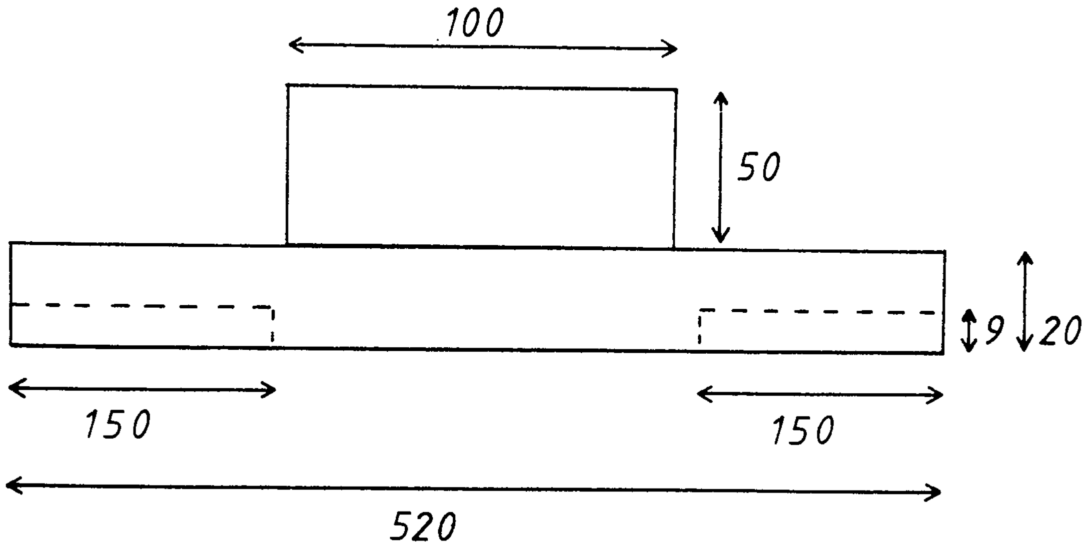
coil to give it a low Q-value and hence some measure of tolerance to variations in component values and line frequency. The circuit Q-value is given by[54]

$$Q = \frac{Wo\ L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}} \qquad (6.7)$$

The natural coil resistance is 47 Ω giving a Q-value of 30 and so a series resistance of 10 K Ω was added to give the tuned coil a Q-value of 0.14. The resonant response of the tuned coil circuit for both these Q-values can be seen in Figure 6.14.

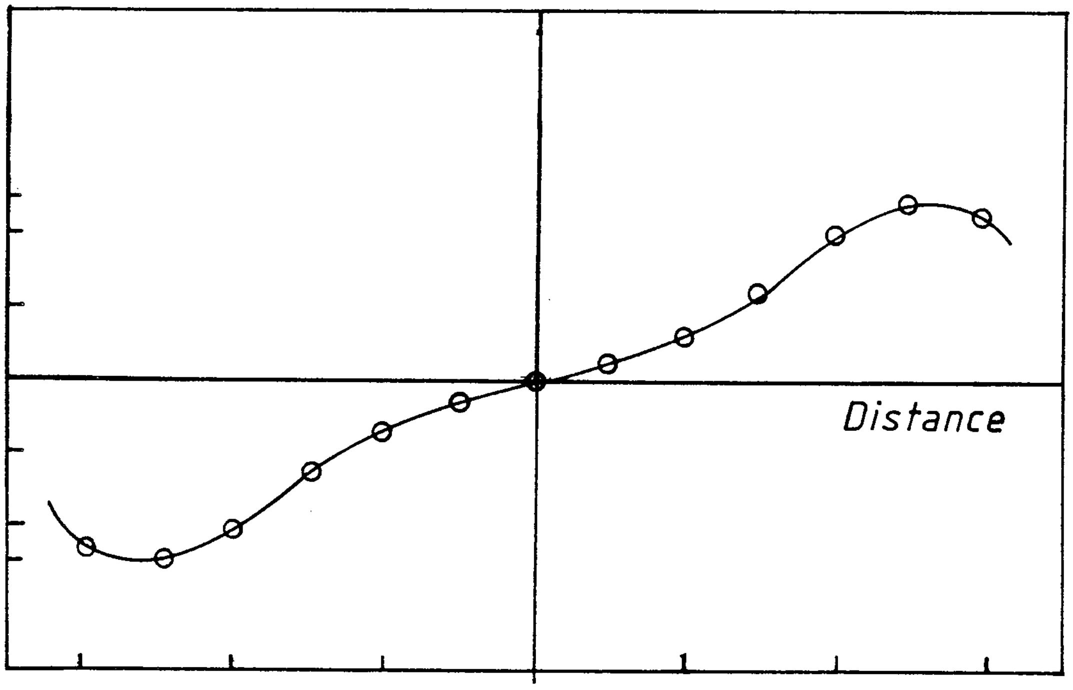
The amplitude distribution of a single coil near a current carrying wire is shown in Figure 7.6. The sharpness of the peak is determined by the length of the coil and to provide a coil with a gentle peak a long coil length was chosen. This also defines the width of the coil since practically only short, fat or long, thin ferrites are available.

The coils presently used are 150 mm long, 9 millimetres in diameter and are fixed in position 60 millimetres above the ground (see Figure 6.15). The spacing of the coils determines the shape of the sensor characteristic and the width of the sensor window, i.e. the region over which the coil difference signal is single-valued. The widest sensor window which can be achieved whilst maintaining a linear sensor characteristic is when the coils are set with a 140 mm gap between the coil ends. In practice a somewhat larger coil separation is used to provide a little deadband stabilisation. The sensor and its characteristic are shown in Figure 6.15.



all dimensions in millimetres

a) Sensor Dimensions



b) Sensor Characteristic

Figure 6.15 - The Lateral Position Sensor

6.6 THE STEERING SYSTEM SOFTWARE

The steering system software has three major tasks to perform: it handles the input from the sensors; it controls both the inner and the outer loops by calculating the error signal ERW and outputing control data to the motor; and it communicates with Vehicle Executive. Three tasks implies three processes, and the software is organised into three sections, a main programme and two interrupt routines. The control loop software is the main programme, and the input software and the communications software are the two interrupt routines. The communications interrupt has priority over the input interrupt and this ensures that a communications request from Vehicle Executive will always be acknowledged as quickly as possible.

6.6.1 The Software Philosophy

The software philosophy is one of structured programming based on the use of functional sub-routines and a database. The programme is divided up into a number of sub-routines all of which perform a certain function. Each routine calls up data which is held in the database, operates on that data and returns any new information generated to the database. Thus for example the difference signal SIG is formed by reading RS and LS from the database and subtracting LS from RS. The software which does this is completely unaffected by any change in the method of generating RS and LS (e.g. a new sensor). Thus this software philosophy is simply another application of the modularity concept. The programming is broken down into separate modules and the use of a database allows storage and retrieval of important system information. The use of the database to supply information to the steering sub-routines also means that external systems (such as Vehicle Executive) can be made to control the steering system. This is done by presenting the database with information to control the steering and setting a flag to let the steering system know that an external processor wishes to override normal system control. If the flag is recognised by the steering software, then it will take the proffered information and put it in the database in place of its own information. Programme execution will then proceed exactly as before, only using the data from the external system. When the external system wishes to relinquish control it simply resets the flag and the steering system returns to using its own calculated data. At present there are three possible sources of steering control; the lateral position sensor, the manual hand controller and the Vehicle Executive, and they all work by putting their own value of SIG in the database. In practice a separate interrupt routine is used for the manual controller because of the need to read in data different to that which is normally read in, but the principle of supplying the database with the required steering information and using the same control sub-routines remains the same. This form of structured programming greatly enhances the reliability of the software. Software reliability is still an undefined science, but in general the more structured a programme is, the more reliable it tends to be. This is because the structure gives a tighter control over the data flow.

Thus the main programme operates on information in the database to provide the closed loop signals and outputs the relevant control data to the motor. As noted in Section 4.4 it can only access the database when a data valid indication has been given by means of an internal flag. This allows the main programme to access the database once only and it cannot access the database again until the flag is set a second time. The flag is set by the input software which is the first of the two interrupt routines. Analogue signals are introduced to the microprocessor through an ADC which digitises the signals so as to present them in a form suitable to the microprocessor. It takes a finite time (64 ms) to digitise the analogue signal and the ADC indicates that it has finished converting the analogue signal to a digital number with an end-of-conversion (EOC) signal. The software merely has to watch for this EOC signal and then read in the data. This, however, is very wasteful of processor time, and it is far better for the processor to be doing something else while the ADC is busy converting and come back and look at the EOC signal every now and again to see if the ADC has finished. This is known as polling and is a valid way of reading in data. The only problem with it is that since there is no synchronisation between the ADC and the microprocessor, the ADC could have been finished for some time before the microprocessor came to look at its EOC signal. This introduces a time delay between the end of converting one sample and the start of converting another. This leads to a reduction in the sampling rate from the maximum possible. This is only a short delay and in situations where the restrictions on sampling are not too severe then polling is an adequate and simple way of reading in data.

In the automatic mode, the input software reads in 32 samples of each coil in order to get a good representative value of the amplitude of the signal in each coil. The frequency of the signal in the coil is 1 KHz and although sampling theory will allow this to be resolved by any sampling rate above 2 KHz, in practice a sampling rate of ten times the input frequency is needed in order to give a reasonable accuracy within a finite time.

If the ADC were run continuously then the 64 ms conversion time implies that a sampling rate of 15.6 K Hz could be achieved. However, after reading in a sample there is a certain amount of data management to perform and a little bit of control needed to start the converter again and so in practice a sampling rate of about 10 KHz is obtained. This rate is perfectly adequate to sample the 1 KHz signal in the coils, but implies that the microprocessor must respond as swiftly as possible to the EOC signal. The delays introduced by polling would be sufficient to affect the accuracy of the data read in by reducing the sampling rate. To achieve this speed of response, the data is read in under an interrupt routine. The microprocessor is programmed to interrupt its normal operation on receipt of the EOC signal, execution of the main programme is suspended and the data is read in, stored, the ADC is restarted and then execution returns to the main programme. The interrupt method is the fastest way of reading in data and ensures that a 10 KHz sampling rate is maintained whilst reading the coils. It should be pointed out that this is not the system sampling time. That is the time taken for one complete pass of the programme and includes reading in two sets of 32 samples, one read of the wheel angle sensor and the control and output of data to the motor. The programme time is 10 ms and this implies a system sampling rate of 100 Hz. The input interrupt is maskable and so can be selectively masked to prevent interrupts. However, interrupts must be enabled at all times so as to keep the communications channel between the steering processor and Vehicle Executive permanently open. Thus in situations where data input is to be prohibited this can only be done by leaving the ADC idle, i.e. not converting. This is required when the main programme first accesses the database. The ADC must be left idle so as not to corrupt data which the main programme is about to use. Thus the main programme accesses the corruptible registers as quickly as possible and then restarts the ADC.

To prevent Vehicle Executive from spending too much time talking to its sub-systems, any communications request from Vehicle Executive must be acknowledged as quickly as possible. For this reason, communications is under interrupt control too. Furthermore, the communications interrupt has priority over the input interrupt, so that as long as interrupts are enabled a communications request will always be swiftly acknowledged by the sub-systems.

Thus the concept of modularity as established for the steering system in Section 4.3 is also applied to the software. It leads to a structured form of software design based on functional sub-routines and the use of a database. The sub-routines are organised into three main sections providing the software for data input, communications and control. The latter section is the main programme whilst the former two sections are interrupt routines. The use of interrupts provides a high enough sampling rate for good resolution of the coil signals and ensures a swift response to any communications request.

6.6.2 The Control Software

A flow diagram of the operation of the control software is given in Figure 6.16. It is the function of the control software to calculate the system error signal ERW and thus control the steering system. It must take account of all incoming data, monitor the flags for external control and output the necessary control signals to the motor. To do this it must access the database and so after first starting the ADC it checks the data valid flag. If the flag is not set, then the programme can do nothing except keep checking the flag. If, however, the flag is set then the programme can move on. It checks the signal level in the coils to determine whether the wire is lost or found. To change the status of the wire flag four successive reads of the new condition are required and this is achieved by the use of a count. This count prevents the steering processor from changing the state of the wire flag on only one reading of the new condition and thus provides some noise immunity to the system. The programme then calculates SIG from the sensor data and overwrites it if external control is indicated. With the required value of SIG, ERW can now be calculated. As evaluted ERW is a twos complement number thus representing both positive and negative numbers. It is immediately turned into a purely positive number and its sign information is recorded in the direction flag. This allows manipulation of the error signal in software (e.g. multiplication) without the complication of a twos complement representation. The control data is now sent out to the motor and the software returns to the start of its cycle where it checks the status of the data valid flag.

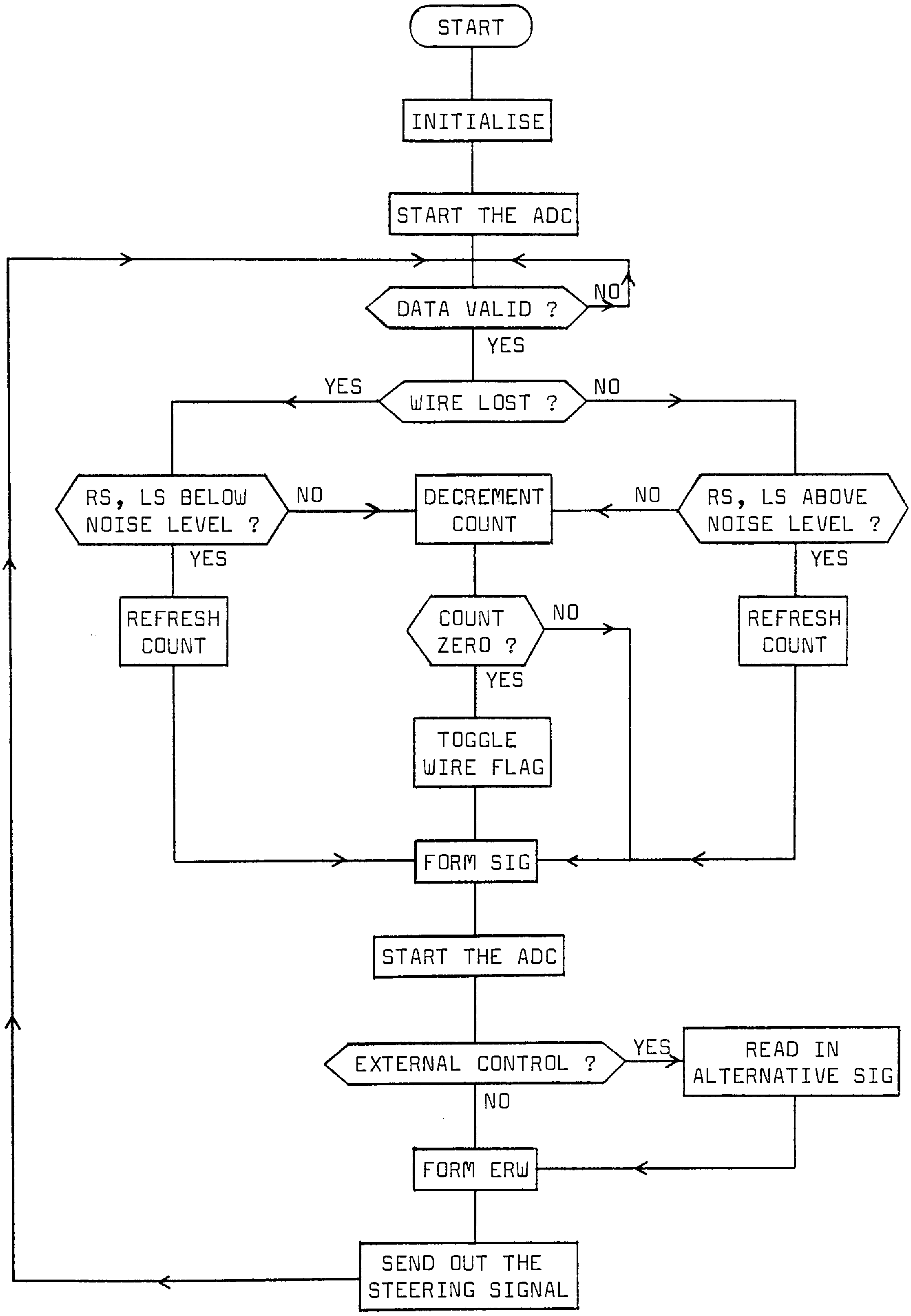


FIGURE 6.16 – THE STEERING SOFTWARE : CONTROL SOFTWARE FLOW DIAGRAM

6.6.3 The Input Software

A flow diagram of the input software is given in Figure 6.17. The input software controls the reading and handling of all the system data inputs. In the automatic mode this consists of the two coils, the wheel angle potentiometer and the manual request line. It also operates the steering system monostable. The interrupt routine is entered on receipt of the EOC signal from the ADC and having read in the data value and performed such data management as necessary, the software restarts the ADC as soon as possible to maintain the sampling rate. The software then finishes its data management (demodulating coil samples, calculating average values, etc), and returns programme execution to the control software. This is in every case except when the last item for one complete batch of data has been read in. Then the software sets the data valid flag and terminates without restarting the ADC. The data valid flag enables the control software to access corruptible database registers before restarting the ADC and hence the next cycle of the input software.

6.6.4 The Communications Software

A flow diagram of the operation of the communications software is given in Figure 6.18. The sub-routines which control the exchange of information are always initiated by Vehicle Executive. In cases where the sub-system wishes to communicate with Vehicle Executive, the sub-system must first tell Vehicle Executive that it wishes to communicate and then wait until Vehicle Executive initiates communications with it. The communications protocol was designed by

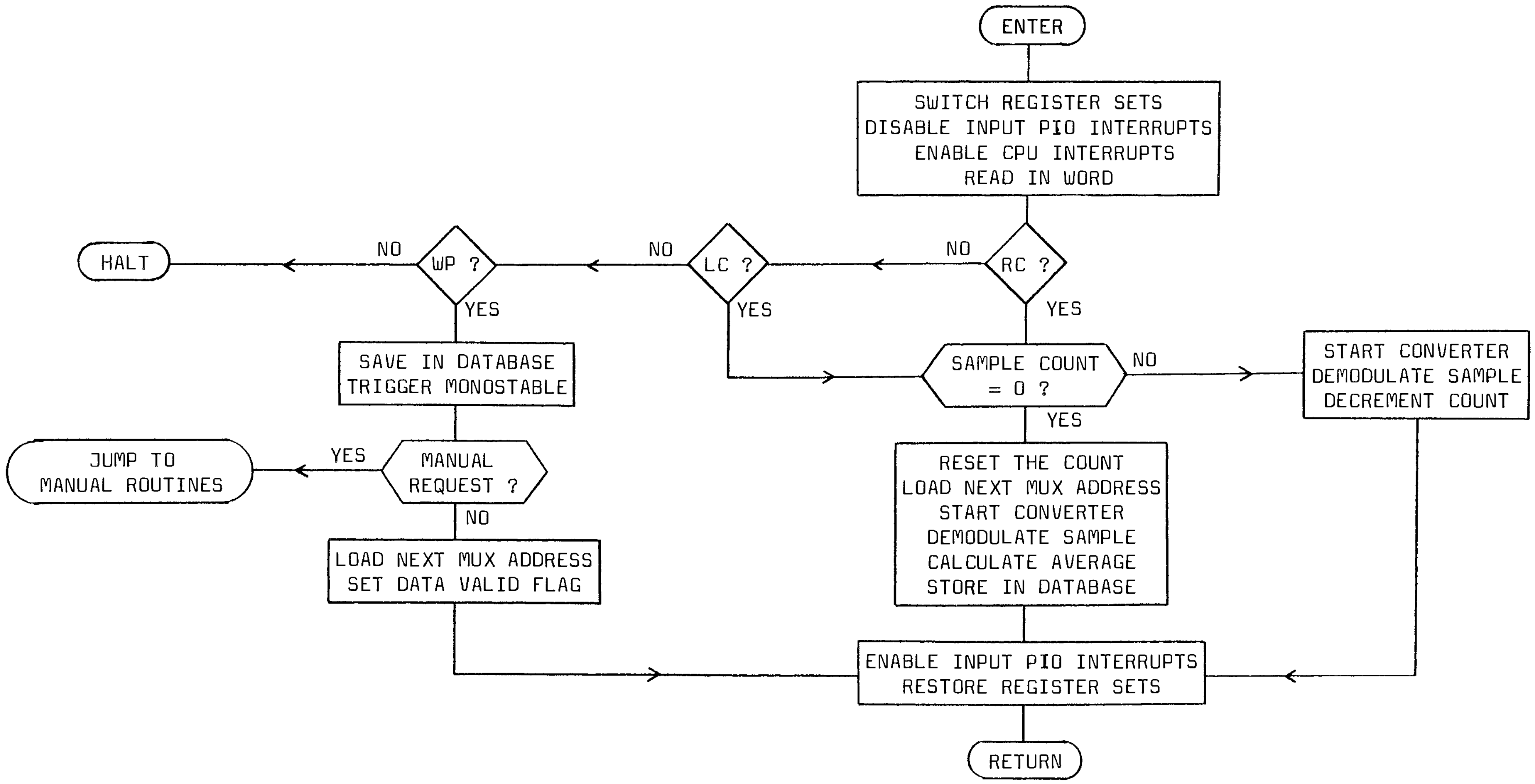


FIGURE 6.17 - THE STEERING SOFTWARE : INPUT SOFTWARE FLOW DIAGRAM

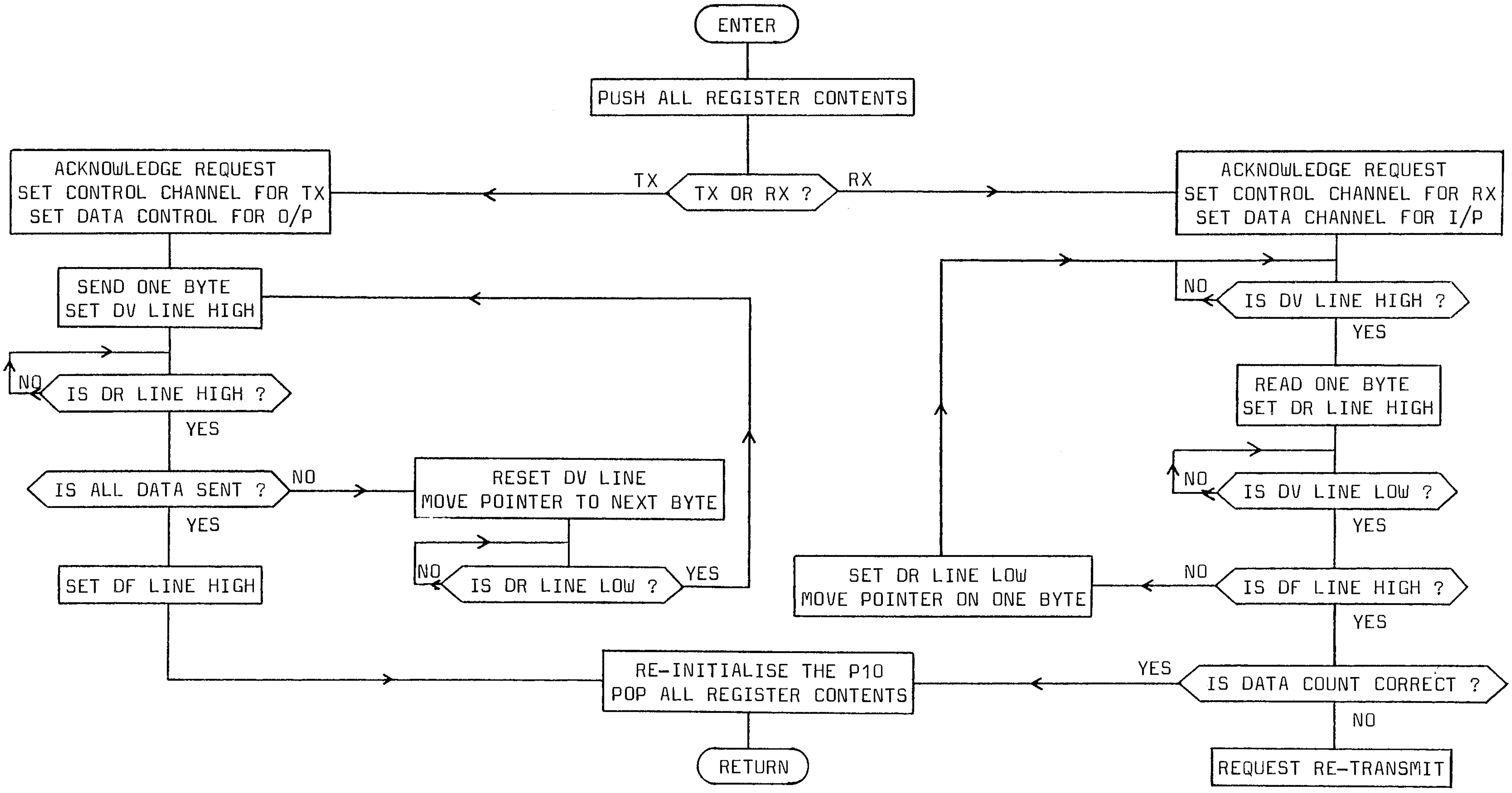


FIGURE 6.18 - THE STEERING SOFTWARE : COMMUNICATIONS SOFTWARE FLOW DIAGRAM

Mr R H Tilbury and written by Miss A Baker. It can be found in Appendix C. There are two major blocks of software, one for transmission (TX) of data from the sub-system to Vehicle Executive and one for receipt (RX) of data by the sub-system from Vehicle Executive. Which block is chosen depends on the state of a communications control word. This is sent out by Vehicle Executive and determines not only the communications mode but also which sub-system processor is involved.

6.7 SUMMARY

The vehicle used as a test platform was originally designed as a rider controlled vehicle and so was not particularly the best test bed for the operation of a riderless vehicle. Neither of the steering motors used was particularly suited to the automatic steering of a vehicle, although the second motor used was better matched to the task than the first. However, despite these drawbacks the vehicle and motors served as useful test beds upon which to investigate the practical consequences of the theory developed earlier. Several stages of electronics led to the establishment of a suitable motor controller and a specification for a steering system. Two sensors were used, these being necessary for the control of the vehicle steering system. The steering software was designed and written according to the modularity concept thus requiring the use of status flags and a database. This gave the software its structured, and hence reliable, form and allows the control of the steering system from any one of three sources.

CHAPTER 7

RESULTS

7.1 OBJECTIVES

The research work described in this thesis has provided four major areas of work. Firstly, it has established a previously non-existent research department at the sponsoring company, and provided that department with a programme of research. This has already been described in Chapter 3. Secondly, the physics of the magnetic sensor used in commercially available wire guidance systems was investigated. This led to a theoretical analysis of the voltages induced in coils near a current carrying wire, results from which have enabled a specification for the magnetic sensor to be developed. Thirdly, an investigation into the steering system was carried out. This involved a theoretical analysis of the system components. The components were then modelled mathematically and the model results compared with measured data. Two steering sub-systems can be conveniently separated and these are: (i) the steering motor in its closed loop angle demand system which places a steering angle on the wheels; (ii) the lateral response of the vehicle to a steering angle placed on its wheels. Finally, on the basis of, and in support of this work, hardware systems were developed and these were evaluated on a test vehicle at the sponsoring company to provide validation for the theoretical analysis. A description of the hardware systems has been given in the previous Chapter.

In this Chapter the results from the theoretical analysis will be presented and compared with the measured results obtained from the hardware systems. This will be done in turn for the magnetic sensor, the steering motor and the vehicle lateral response. Validation of the vehicle lateral response model will then allow the simple theory developed in Chapter 5 to be extended to include the effects of wire curvature. This will allow some aspects of the system stability to be investigated before leading to a presentation of the complete system model.

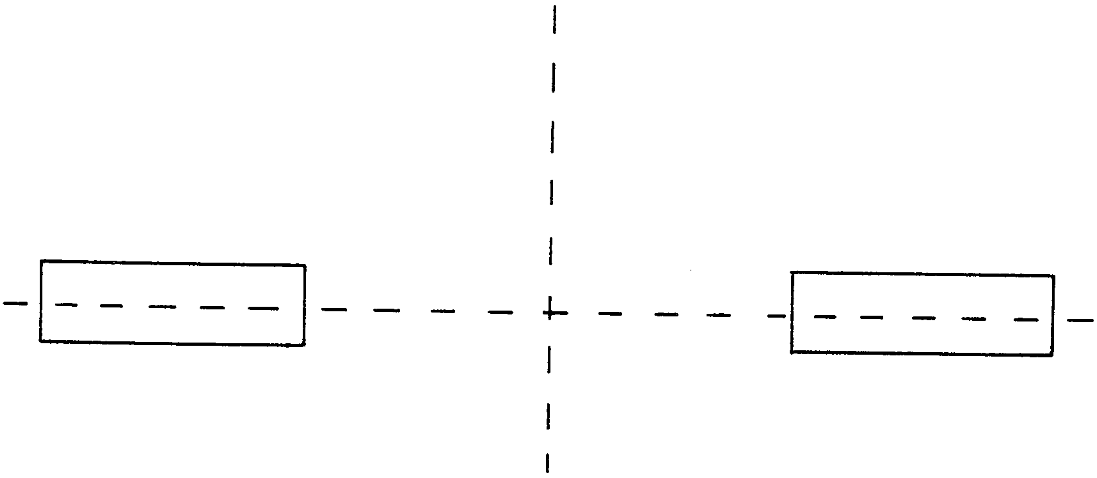
7.2 THE MAGNETIC SENSOR

The magnetic sensor consists of two coils situated either side of a current-carrying wire. The theory has already been presented in Section 5.5 and some of the practical details have been given in Section 6.6. This section will present the details of the sensor response and the results from the computer programmes developed in support of the theory.

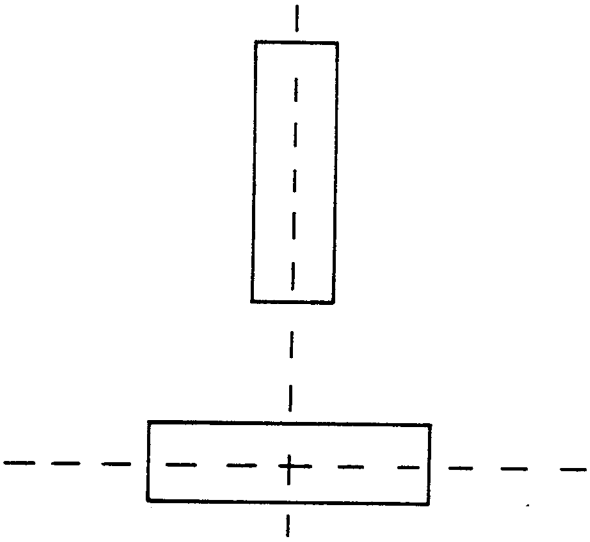
Firstly, the response of a search coil in both horizontal and vertical orientations is considered. The extension of the search coil to a finite coil is then considered, and finally the use of two coils to make a sensor is presented.

7.2.1 The Search Coil

Although the use of two horizontal coils which straddle the guide wire is used universally as a steering sensor[10-14] there is nowhere information available to support this decision or in any way justify it. Another possible sensor configuration could be to have the two coils together in the centre of the vehicle in an inverted-T configuration. As the coils cross from one side of the wire to the other, the phase of the vertical coil changes by 180^{o} but the phase of the horizontal coil does not. Thus the output of the vertical coil can be used to provide the magnitude information of a steering signal and its phase relation to the output of the horizontal coil can provide the sign information. The two possible configurations are shown in Figure 7.1. To investigate the characteristics of these two configurations a small search coil was built with a radius of 5.5 mm and a length of 12 mm. The voltages induced in the search coil for both vertical and horizontal orientations were then plotted against distance and can be seen in Figure 7.2. These are of course the individual coil voltages. To form the complete sensor characteristic for the vertical coil, its output is phase compared with a reference to provide sign information which will have the effect of inverting one side of the characteristics. For the horizontal coil, it is slightly more complicated, requiring the subtraction of another coil voltage from the one given. The question of the shape of the characteristic for the horizontal configuration will be considered in more detail in sub-section 7.2.3. However, the resulting shape is essentially that already given in Figure 2.2. The shapes of the sensor characteristic for each of the two sensor configurations are shown in Figure 7.3. It is the region around the origin which is of interest and here a linear, single-valued characteristic is required. Referring to Figure 7.3, it can be seen that both configurations provide this over a limited range, but that the horizontal configuration has a much wider single-valued response than does the inverted-T design. For this reason, the horizontal configuration is to be preferred. It also has the advantage that in the zero position (i.e. over the wire) both coils have definite voltages in them which makes recovery of the signal much better in



a) Horizontal Configuration



b) Inverted-T Configuration

Figure 7.1 - Sensor Configurations

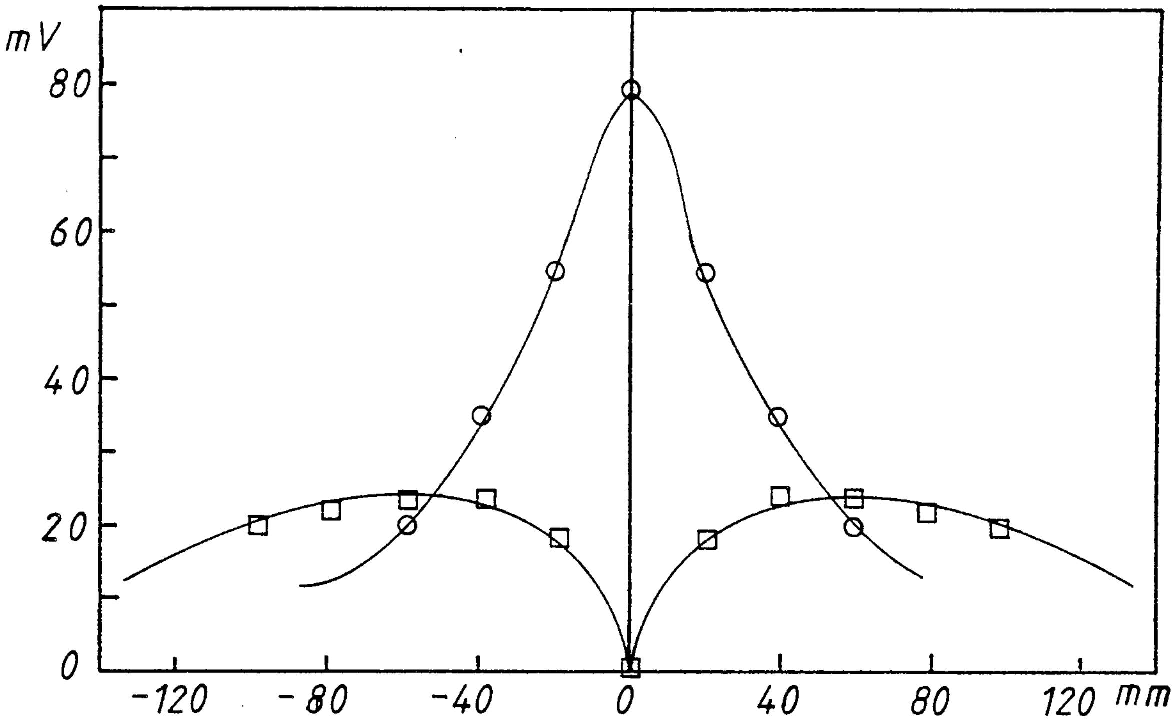


Figure 7·2 - Search Coil Voltages
○ Horizontal Coil
□ Vertical Coil

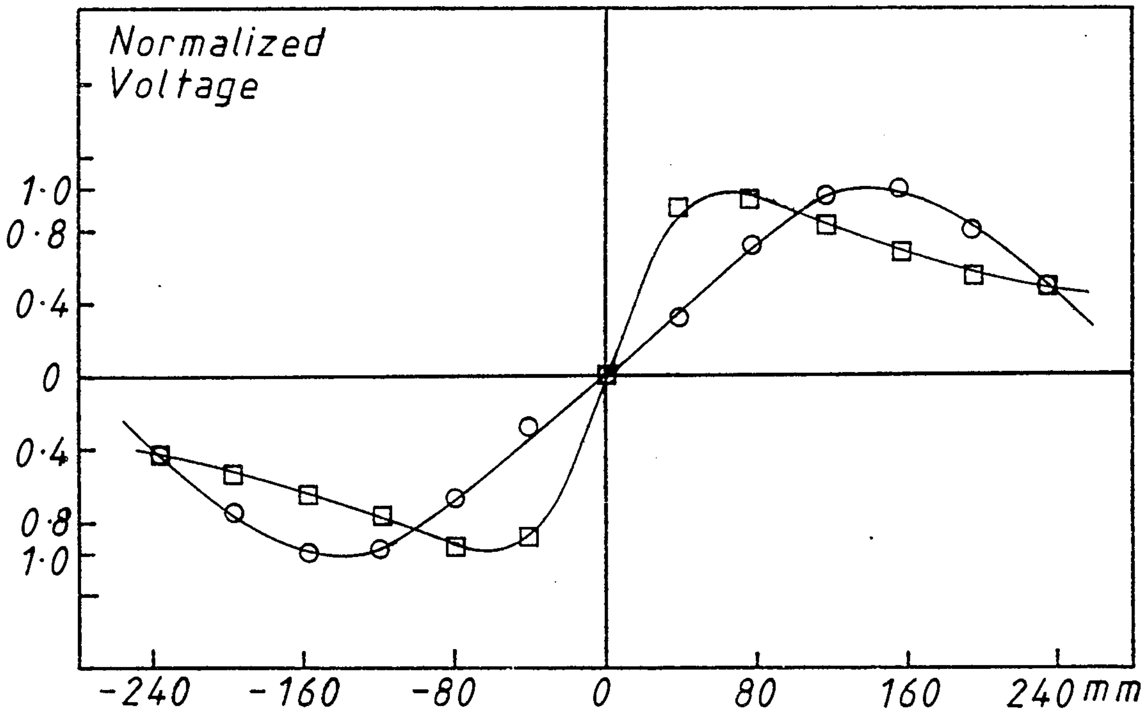


Figure 7·3 - Sensor Characteristics
○ Horizontal Configuration
□ Inverted-T Configuration

noisy conditions than the inverted-T configuration where the amplitude information is zero. The only disadvantage is that it is bigger than the inverted-T design.

A computer programme based on the theory developed in Section 5.4 has been developed to calculate the voltages induced in a search coil in either a horizontal or a vertical orientation. Results from it are shown in the graphs in Figures 7.4 and 7.5 where they are compared with the measured results from Figure 7.2. As can be seen the agreement is good thus providing validation for the theory upon which the programme is based.

7.2.2 The Finite Coil

In industrial environments electrical noise is always present and acting to degrade the signal received from the steering sensor coils. In any electrical system, the best way to improve the signal-to-noise ratio is to increase the signal strength right at the input, and so for this reason, finite length coils wound with multiple layers on ferrite rods are used in place of the simple search coil. The output from a coil of the same dimensions as those used in the steering sensor (see Section 6.6 for details) is shown in Figure 7.6 where it is compared with the theoretical value calculated from the programme based on the theory. The programme will work out either the voltage induced in a single coil with the centre of the coil at each point for which a value is calculated, or the voltage induced in a coil assembly with the centre of the assembly at each point for which a value is calculated. The programme is similar to the search

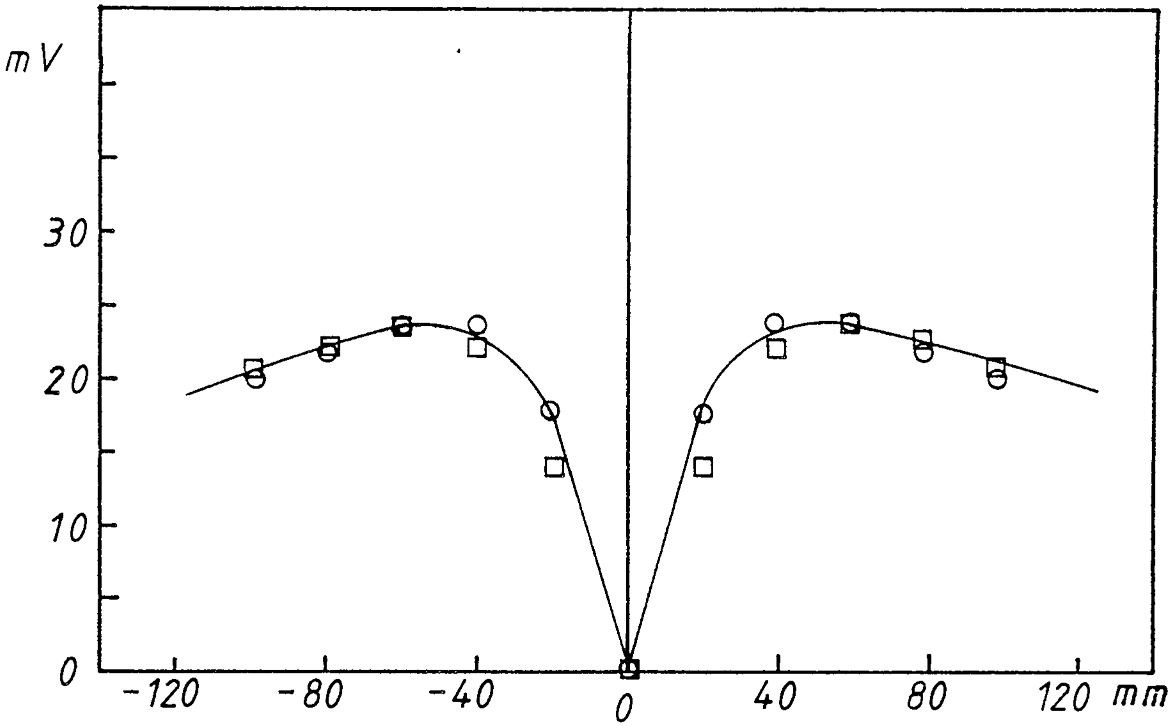


Figure 7·4 - Search Coil Voltages - Vertical Coil
Comparison of Measured
& Theoretical Values
○ Measured □ Theoretical

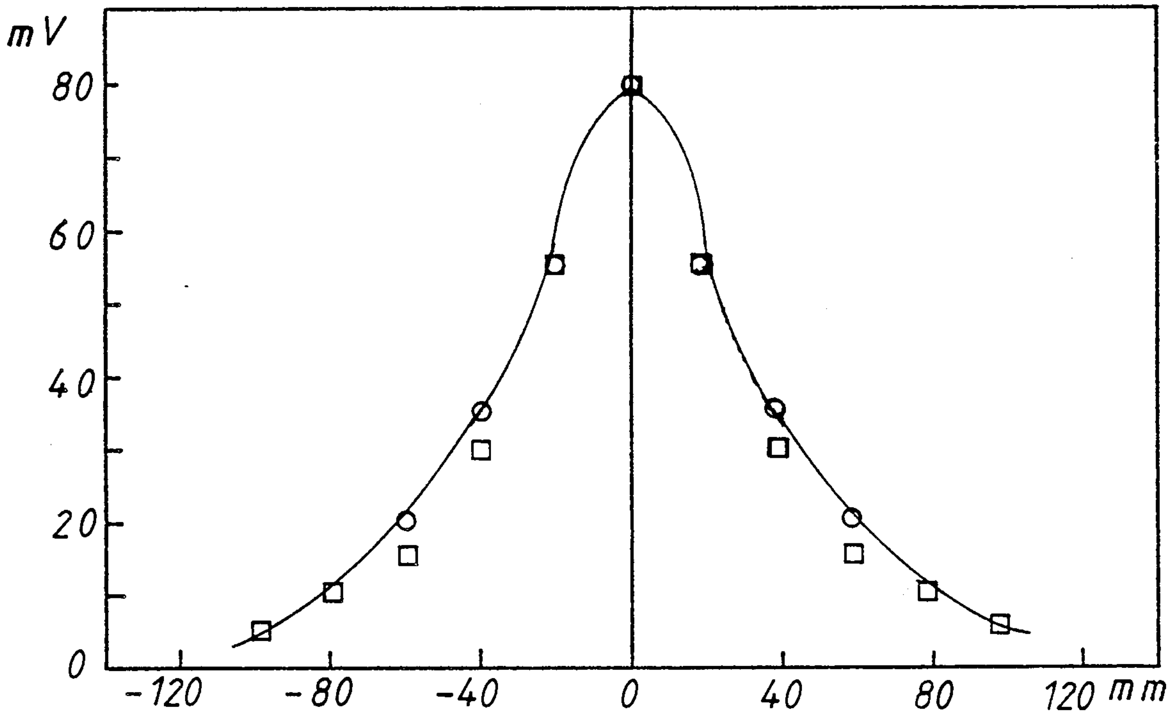


Figure 7·5 - Search Coil Voltages - Horizontal Coil
Comparison of Measured
& Theoretical Values
○ Measured □ Theoretical

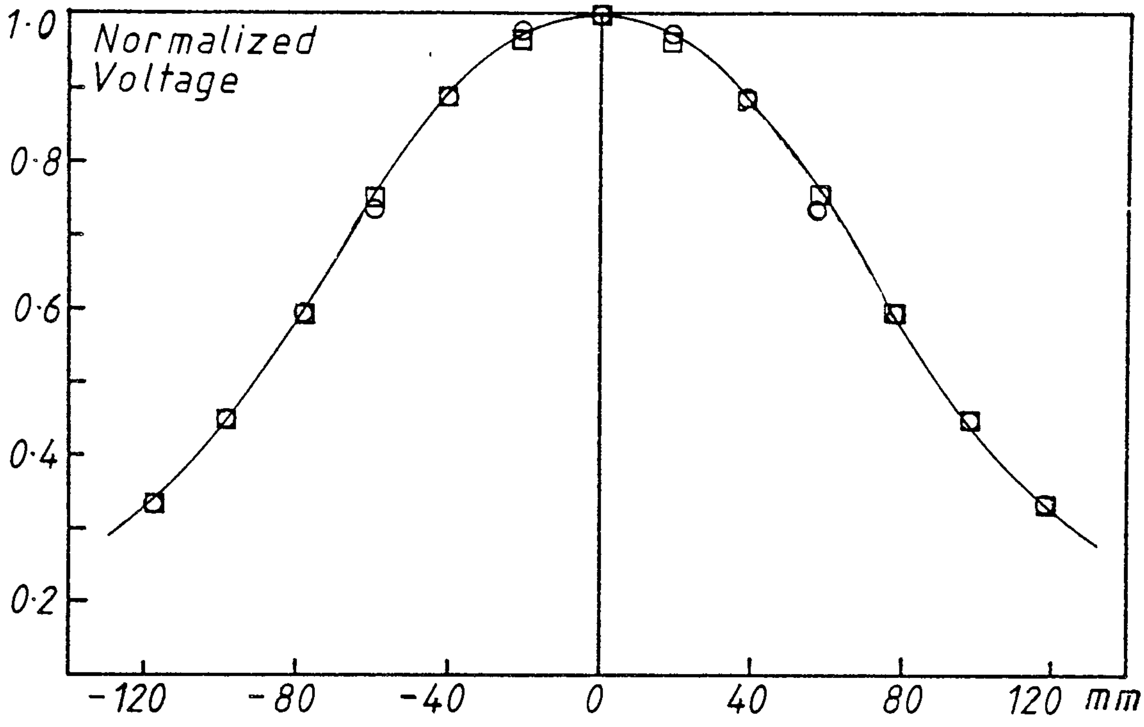


Figure 7·6 – Finite Coil Voltages
Long Thin Coil
○ Measured □ Theoretical

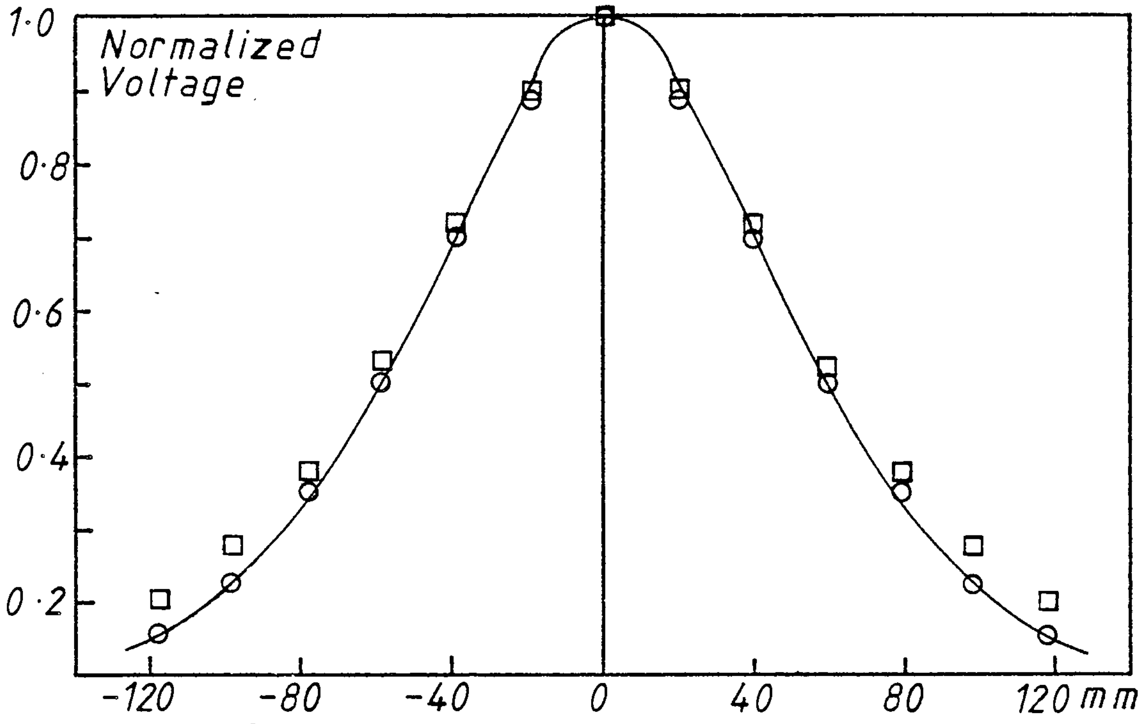


Figure 7·7 – Finite Coil Voltages
Short Fat Coil
○ Measured □ Theoretical

coil programme differing only in those extra details needed to cope with the complexity of a coil of finite length or a coil assembly. Referring to Figure 7.6, the close agreement between the measured and theoretical values for a single coil can be seen thus validating the programme and the theory upon which it is based. The programme was also run for a coil of different dimensions, and the comparison between the measured and the theoretical values can be seen in Figure 7.7. Again the agreement is good.

With the theory thus validated, the programme was used to investigate the effect of various parameters on the output voltage from the coil. The parameters varied were coil length, coil radius, the height of the coil above the wire, the number of turns per unit length, the frequency in the wire, and the current in the wire. The effect of varying each parameter was investigated by comparing the coil output for a standard run (based upon the short fat coil) with the output for a calculation where only one parameter had been altered. The parameter of interest was always doubled, except the height of the coil above the wire, which was halved. The results can be seen in Figure 7.8, and can be quite easily understood if the expression for the output voltage from a single, finite coil is considered. Recalling equation 5.56

$$Em = \int_{o}^{l} \int_{-r}^{r} \frac{w\ \mu o\ \mu r\ nIm\,(h + y)\sqrt{r^2 - y^2}\ .dy.dz}{\pi\ (z^2 + (h + y)^2)} \qquad (5.56\ \text{repeated})$$

shows that the number of turns per unit length n, the current i and the frequency w are simple multiplier terms. Thus the effect of doubling these parameters will be a simple doubling of the output voltage as can be seen in Figure 7.8. Doubling the radius has the

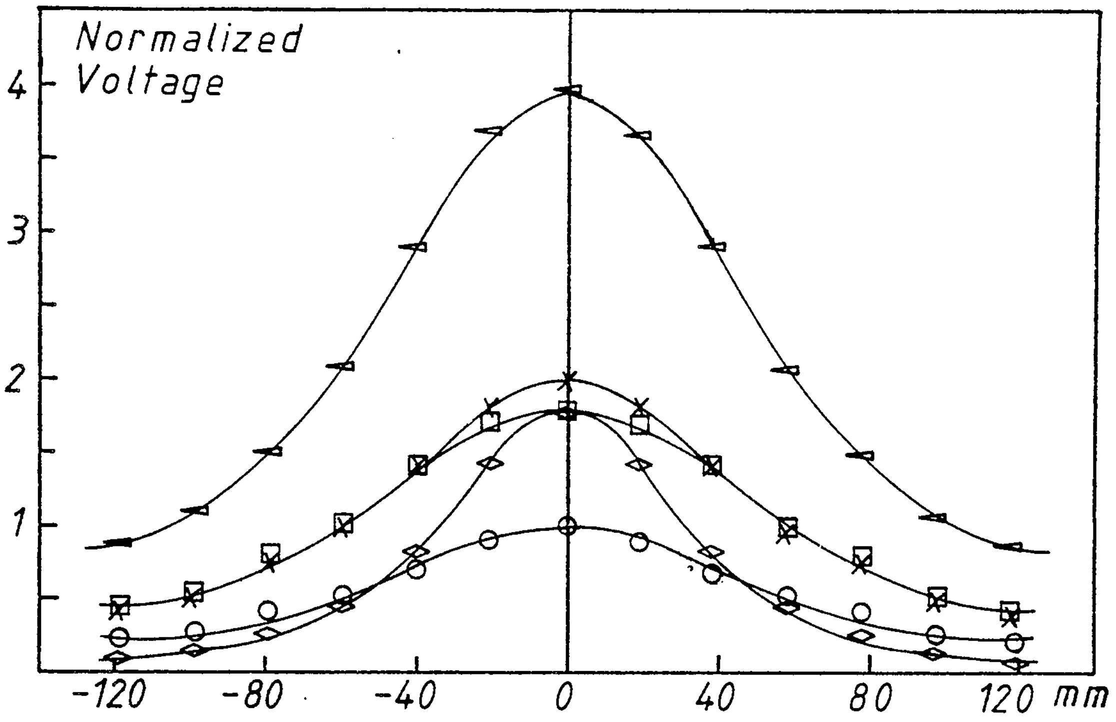


Figure 7·8 - Coil Parameter Sensitivities
○ Standard Run
□ Double Length
◅ Double Radius
× Double Current, Frequency & Turns
◇ Half Height

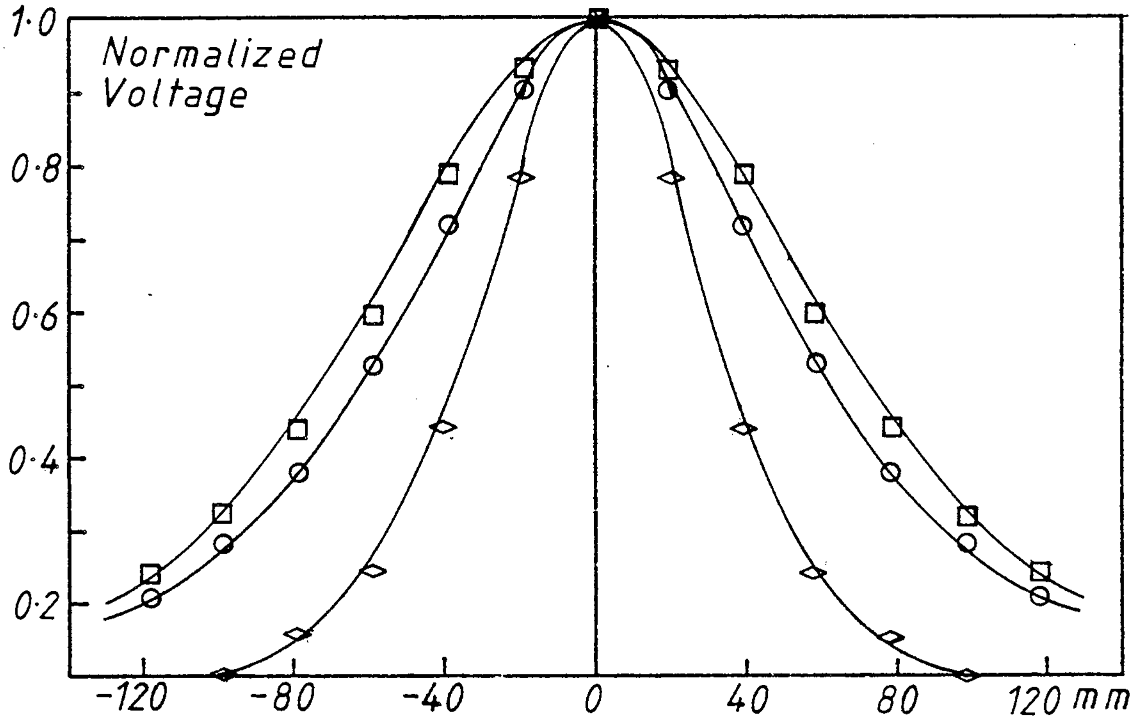


Figure 7·9 - Normalized Coil Outputs
○ Standard Run
□ Double Length
◇ Half Height

effect of increasing the volume of the coil by a factor of four and so will increase the coil output by the same amount. Decreasing the height of the coil will increase the coil output when the coil is directly over the wire, since it is now closer to the wire, but as the coil moves laterally away from the wire, its output will die away much quicker. This is because it moves more quickly into the area where the lines of flux of the field are at right angles to the axis of the coil and thus are not sensed by the coil. Increasing the length of the coil has the effect of reducing the rate of decay of the coil response since a section of the coil stays in the area of high normal flux much longer than with the shorter coils. This can be seen much more clearly in Figure 7.9 which shows the normalised outputs for various different dimension coils, thus displaying the shape of the response rather than the magnitude of the response. As can be seen the only two factors which change the shape of the response are the length of the coil and the height of the coil above the wire. As explained above, increasing the length of the coil reduces the rate of decay of the coil response and reducing the height of the coil above the wire increases the rate of decay of the coil output. All the other parameters affect the gain only.

Thus the theory adequately explains how the voltages induced in a coil in the field of the guide wire alter as various parameters are changed. This can lead to a specification for the shape of coil to be used, but to do this the response of two coils, acting together as a single sensor must be considered.

7.2.3 The Guidance Sensor

Figures 7.10 and 7.11 show comparisons of measured and theoretical sensor characteristic for sensors with two different shapes of coil. One is a long, thin coil of length 150 mm and radius 5 mm; the other is a short fat coil of length 40 mm and radius 9 mm. The close agreement between the two sets of curves provides further validation for the theory and the programme. The programme was used to investigate how the separation of the two coils affected the output characteristic of the sensor. The sensor consists of two identical coils whose voltages are applied in opposition. This is shown in Figure 7.12a where the two coils, and their associated voltage characteristic are shown, separated by a large distance such that the voltages do not overlap. As the coils are brought closer together, the voltages begin to overlap producing firstly a sensor characteristic such as Figure 7.12b, and as they get closer still, the characteristic becomes more and more linear until at the point when the coil separation equals the coil length, a linear characteristic, such as Figure 7.12c, is achieved. If the coils are brought closer still, the characteristic remains linear, but the slope increases and the range over which it is single valued, becomes less.

To derive a specification for the shape of the coils used and their separation in the sensor, it is necessary to know what sort of characteristic is required from the sensor. The sensor characteristic should have a linear profile over as wide a range as possible. Too narrow a range, or sensor window, will mean that the steering system is unduly sensitive to small lateral deviations and

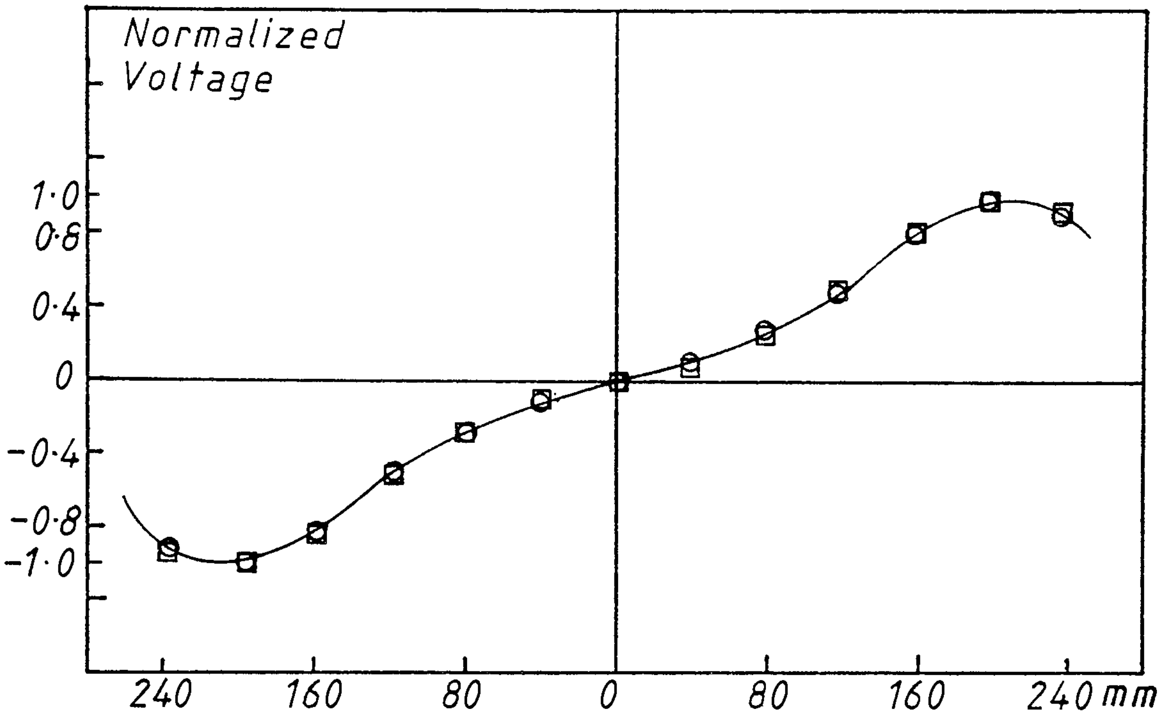


Figure 7·10 - Sensor Characteristic
Long Coils
○ Measured □ Theoretical

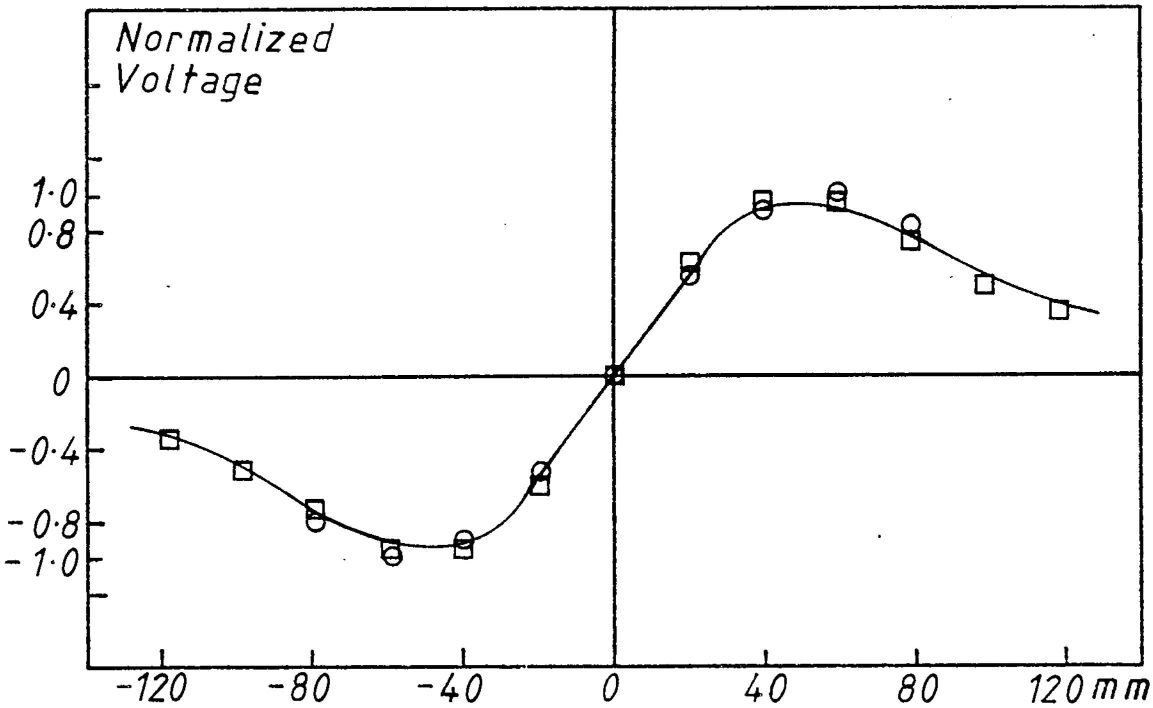
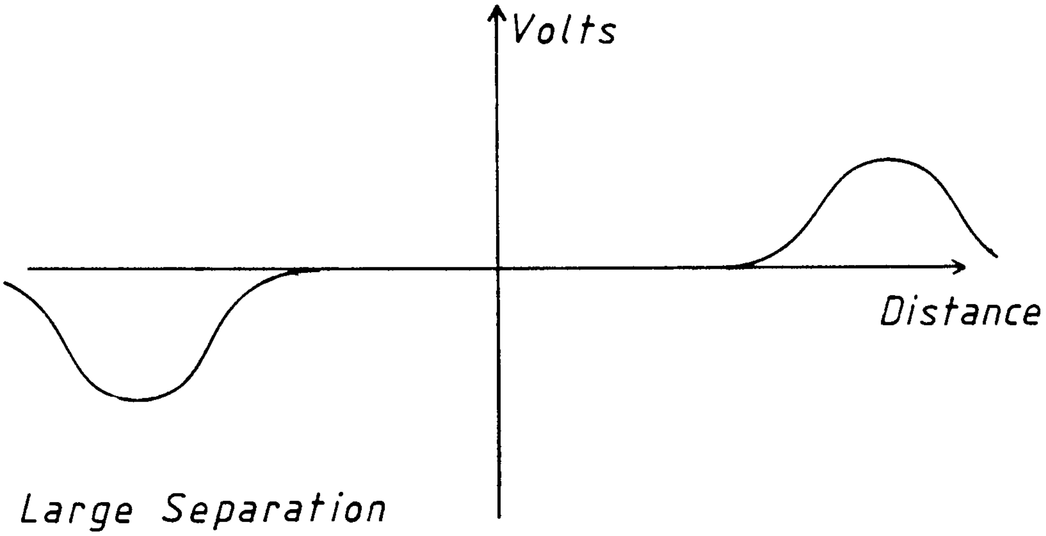
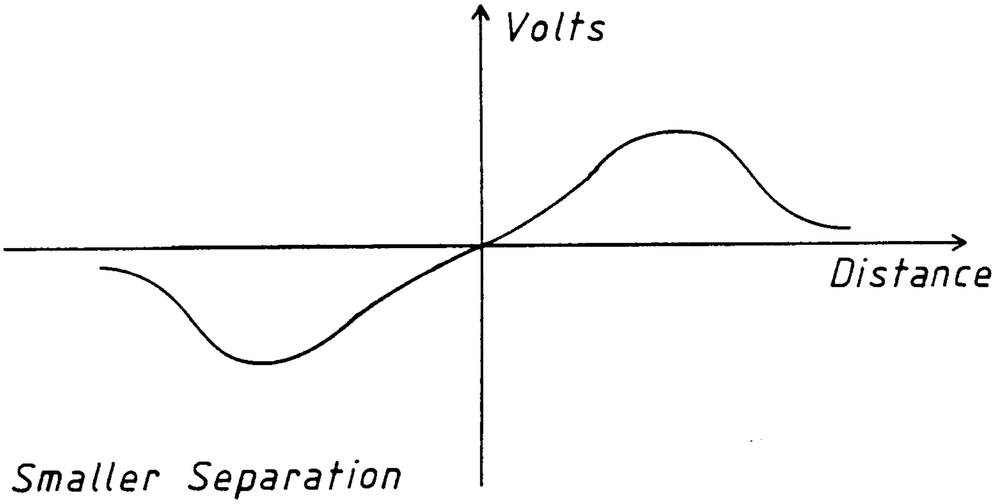


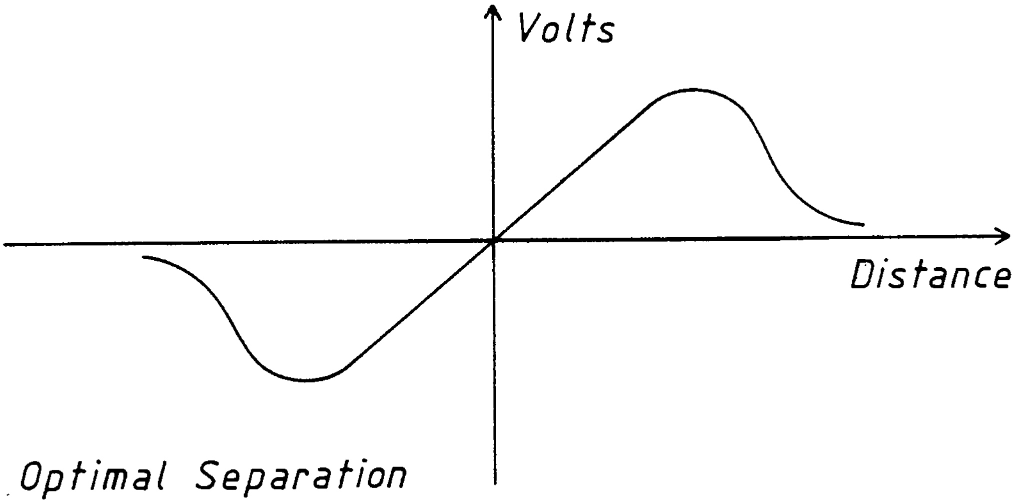
Figure 7·11 - Sensor Characteristic
Short Coils
○ Measured □ Theoretical



a) Large Separation



b) Smaller Separation



c) Optimal Separation

Figure 7·12 - The Effect of Coil Separation on the Sensor Characteristic will cause jitter or small high frequency (≅ 2Hz) oscillations in the wheel position. However, if the window is opened too wide, such as in Figure 7.12a, then the system tends to behave as an on-off control system where the only possible values of wheel angle are straight ahead or full lock. This leads to violent low frequency oscillations of the truck of large amplitude. Thus the ideal shape of sensor characteristic is as wide a window as can be achieved without sacrificing the linear slope. In practice, a small amount of flattening in the centre of the characteristic can give a little deadband stabilisation and thus be quite useful but this should not be excessive. A plot of the sensor characteristic used on the vehicle is given in Figure 7.10. The sensor window is 400 mm and over this range short coils cannot provide the linearity of characteristic required because their output voltage decays too quickly as the centre of the coil moves off the wire. To provide the width of sensor window and maintain a reasonable level of signal over the whole of the window, long coils are required where the rate of decay of voltage as the coil moves off the wire is not too rapid. Furthermore, the coils must not be too close to the ground as this increases the rate of decay of output voltage.

Thus the shape of the sensor characteristic presents a requirement for long coils which are not placed too close to the ground. The remaining parameters are decided by gain considerations. To give a good signal-to-noise ratio for the sensor, the other parameters must be chosen to maximise the output from the coils. Thus the coils should have a large radius and a large number of turns and the wire should have as high a frequency and as large a current in it as possible. This theoretical specification is however subject to practical considerations. Readily available ferrites come in two shapes; short and fat or long and thin. Thus the requirement for a long sensor immediately sets the coil radius. Increasing the number of turns on the ferrite increases the coil resistance and self-capacitance to a point where its own resonant frequency interferes with the wire frequency. This limits the number of turns on the coil. The wire frequency is set by the sample rate of the ADC which limits it to around 1 kHz, although if the coil amplitudes were recovered in hardware this could be increased. However, the wire frequency must be kept below the resonant frequency of the coils and in commercial practice wire frequencies do not go above 10 kHz. Furthermore, this keeps the wire frequency well out of commercially used radio bands. Finally, the more current sent down the wire, the more the wire will broadcast and present possible interference to other electromagnetic equipment. Thus the wire current should be as low as is commensurate with safe operation of the steering system in noisy conditions.

The sensor is shown in Figure 6.15 where it can be seen that the coils are 150 mm long, 9 mm wide and at a spacing of 220 mm thus giving the characteristic a slight deviation from the linear to provide a little stabilisation. The measured characteristic from this sensor is shown in Figure 7.10 and the approximate slope Ks is given by

$$Ks = \frac{188 - 72}{0.2 - (-0.2)} = 290 \text{ mm}^{-1} \qquad (7.1)$$

Now the resolution of the analogue-to-digital converter is 20 mV. Thus the sensor gain is given by

$$Ks = 290 \cdot 20 \cdot 10^{-3} = 5.8 \text{ V m}^{-1} \tag{7.2}$$

7.3 THE STEERING MOTOR

The CAV motor was too low powered to act as a steering motor. The results taken while using this motor were dominated by friction and were thus not particularly informative as regards the system response. Accordingly, the results presented in this section will be for the NECO motor only. Furthermore, since the same tests were run on each different controller, then generally only those results for the mark 2 armature controller will be presented. However, where appropriate these results will be compared with those from other controllers to show the difference between the various controllers.

Validation of the programme written in support of the theory will be achieved by comparing measured and theoretical results and will follow the pattern of theory development: i.e. firstly, the open loop response to speed will be looked at; then the open loop response to position; and finally the closed loop response to position.

7.3.1 Armature Volts to Motor Speed

To provide the data for the Pf vs Bm curve (Figure 6.8), the motor was subjected to a number of voltage step inputs of 24 V at various field strengths. After the transient response had died down, the steady state value of all the system parameters, and in particular the armature current Ia and the armature shaft speed w, were taken. A programme to model the motor behaviour from armature volts to speed on a state space basis using the two state variables Ia and w was written. The programme was run for four different values of field current, and the results can be seen, compared with the measured results, in Table 7.1. Also shown in Table 7.1 are the results from another programme, which models the motor using the single state variable w and neglecting the armature inductance. As can be seen, both programmes give results which agree quite closely with those measured.

The single variable programme has two advantages over the two variable programme. By neglecting the armature inductance and thus reducing Ia from a state variable to a parameter, it is less complex. But more importantly, by neglecting the armature inductance and thus the armature time constant, Ta, only the mechanical time constant T_L remains. Since T_L is much larger than Ta, the sampling time of the discrete equations can be increased. For the two variable programme the sample time is 5.10^{-4} s and for the single variable programme it is 1.10^{-2} s. This makes it much quicker to run. The sample time in the two variable programme is so small because the armature time constant Ta is 4.10^{-3} s. As was noted in Section 5.5 the sample time has to be of the order of 1/10 the size of the smallest system time constant. If the sample time is larger than a system time constant, then instability occurs and this can be seen quite clearly in Table 7.2 which shows the results from the two variable programme for two different values of sample time, one of which is larger than Ta. Conversely, Table 7.3 shows the same

I_f	MEASURED		CALCULATED		
	I_a	w	2 VARIABLES		1
			I_a	w	w
1.9	2.30	171.15	2.34	172.17	172.17
1.5	2.20	184.80	2.24	186.02	186.02
1.0	2.39	231.00	2.41	229.40	229.40
0.5	3.65	346.50	3.70	344.40	344.40

TABLE 7.1: STEADY STATE VALUES OF I_a AND w
MEASURED, CALCULATED

```
Ok
RUN


For If= 1.9 amps & sample time = 5E-04 secs

   Ia             Speed           Time

 38.29            112             .05
 13.67            153.2           .1
 5.91             166.19          .15
 3.47             170.28          .2
 2.7              171.57          .25
 2.45             171.98          .3
 2.38             172.11          .35
 2.35             172.15          .4
 2.35             172.16          .45
 2.34             172.16          .5
 2.34             172.17          .55
 2.34             172.17          .6
 2.34             172.17          .65
 2.34             172.17          .7
 2.34             172.17          .75
 2.34             172.17          .8


For If= 1.9 amps & sample time = .01 secs

   Ia             Speed           Time

 535.51           39.53           .05
-2156             506.79          .1
 9352.81         -1336.04         .15
-40328.9          6661.67         .2
 174010          -27830.9         .25
-750736           120987          .3
 3.23899E+06     -521074          .35
-1.39743E+07      2.24904E+06     .4
 6.02907E+07     -9.70233E+06     .45
-2.60118E+08      4.18606E+07     .5
 1.12225E+09     -1.80603E+08     .55
-4.84186E+09      7.79193E+08     .6
 2.08897E+10     -3.36175E+09     .65
-9.01266E+10      1.4504E+10      .7
 3.88842E+11     -6.25759E+10     .75
-1.67762E+12      2.69977E+11     .8


Table 7.2 - The Effect of Sample Time on the
            Stability of the Discrete Equations -1


Ok
```

```
Ok
RUN


For If= 1.9 amps & sample time = 5E-04 secs

 Speed         Time

  112.1        .05
  151.21       .1
  164.85       .15
  169.61       .2
  171.28       .25
  171.85       .3
  172.06       .35
  172.13       .4
  172.15       .45
  172.16       .5
  172.16       .55
  172.16       .6
  172.16       .65
  172.16       .7
  172.16       .75
  172.16       .8


For If= 1.9 amps & sample time = .01 secs

 Speed         Time

  119.02       .05
  155.76       .1
  167.1        .15
  170.6        .2
  171.68       .25
  172.02       .3
  172.12       .35
  172.15       .4
  172.16       .45
  172.16       .5
  172.17       .55
  172.17       .6
  172.17       .65
  172.17       .7
  172.17       .75
  172.17       .8


Table 7.3 - The Effect of Sample Time on the
            Stability of the Discrete Equations-2


Ok
```

results for the single variable programme whose only time constant T_L is 0.26 s and this is stable.

A programme was written based upon the single variable programme but including extra details to allow the model to be run for a sinusoidal armature voltage of various frequencies thus providing a frequency response plot. A Bode plot of the response can be seen in Figure 7.13 where it is compared with the measured result. Recalling equation 5.12, the d.c. gain value and time constant are approximated by

$$K_1 = \frac{1}{Bm} \quad \text{and} \quad T_1 = \frac{Ra\ J}{Bm^2} \qquad \text{(5.12 repeated)}$$

Putting in the values from Section 6.3 gives

$$K_1 = 7.14 \quad \text{and} \quad T_1 = 0.26 \qquad (7.3)$$

For the Bode plot, the low frequency magnitude M is 20 log K_1 and the breakpoint frequency fb is given by

$$fb = \frac{1}{2\ \pi\ T_1} \qquad (7.4)$$

i.e.

$$M = 17\ \text{dB} \quad \text{and} \quad fb = 0.62\ \text{Hz} \qquad (7.5)$$

and this agrees closely with both the measured and the model results.

The effect of varying the field is shown in Figure 7.14 which shows the same response as Figure 7.13 except the field is now only supplied with 12 volts instead of 24 volts. This gives a Bm value of 0.1 (see Figure 6.10) and thus the low frequency magnitude and

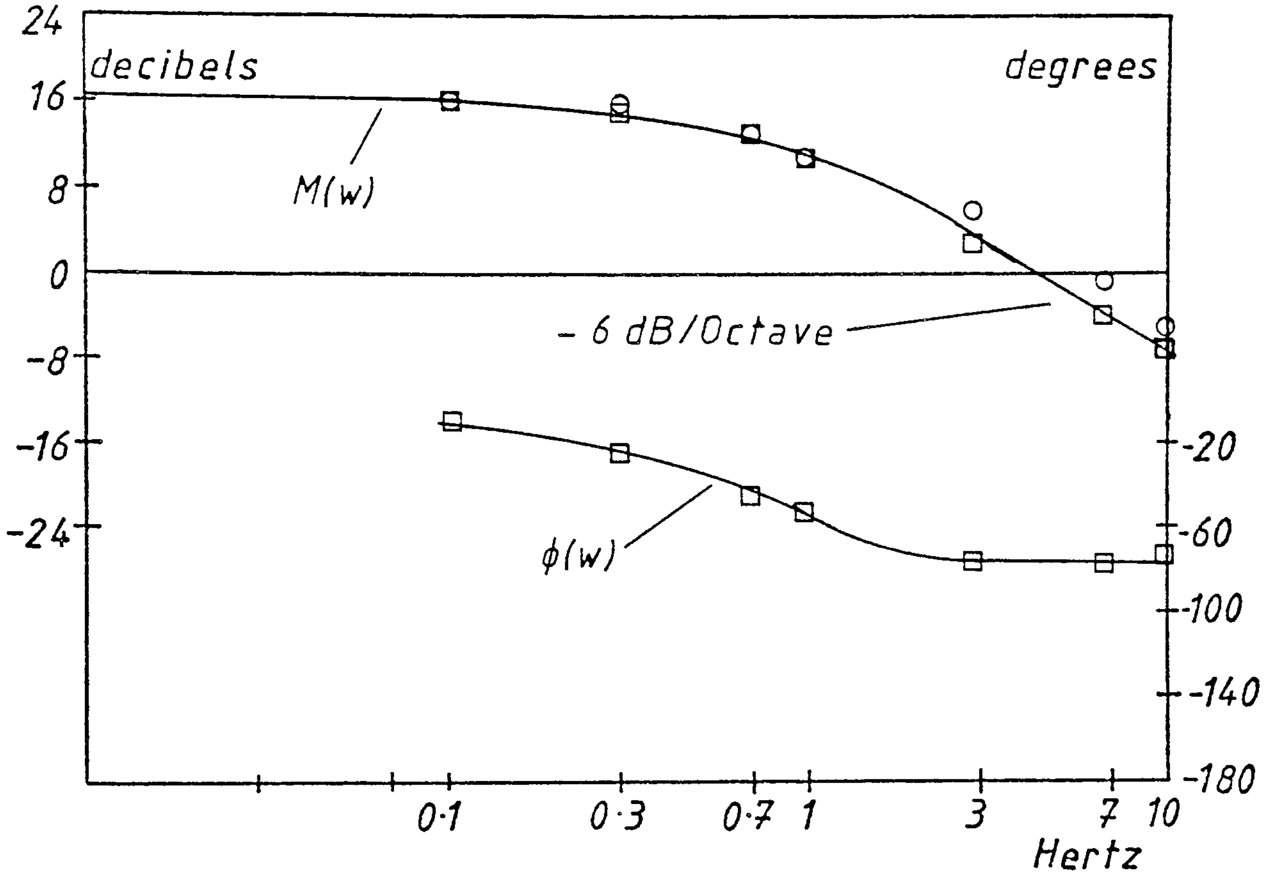


Figure 7·13 -Motor Frequency Response
Armature Volts to Speed - Full Field
○ Measured □ Theoretical

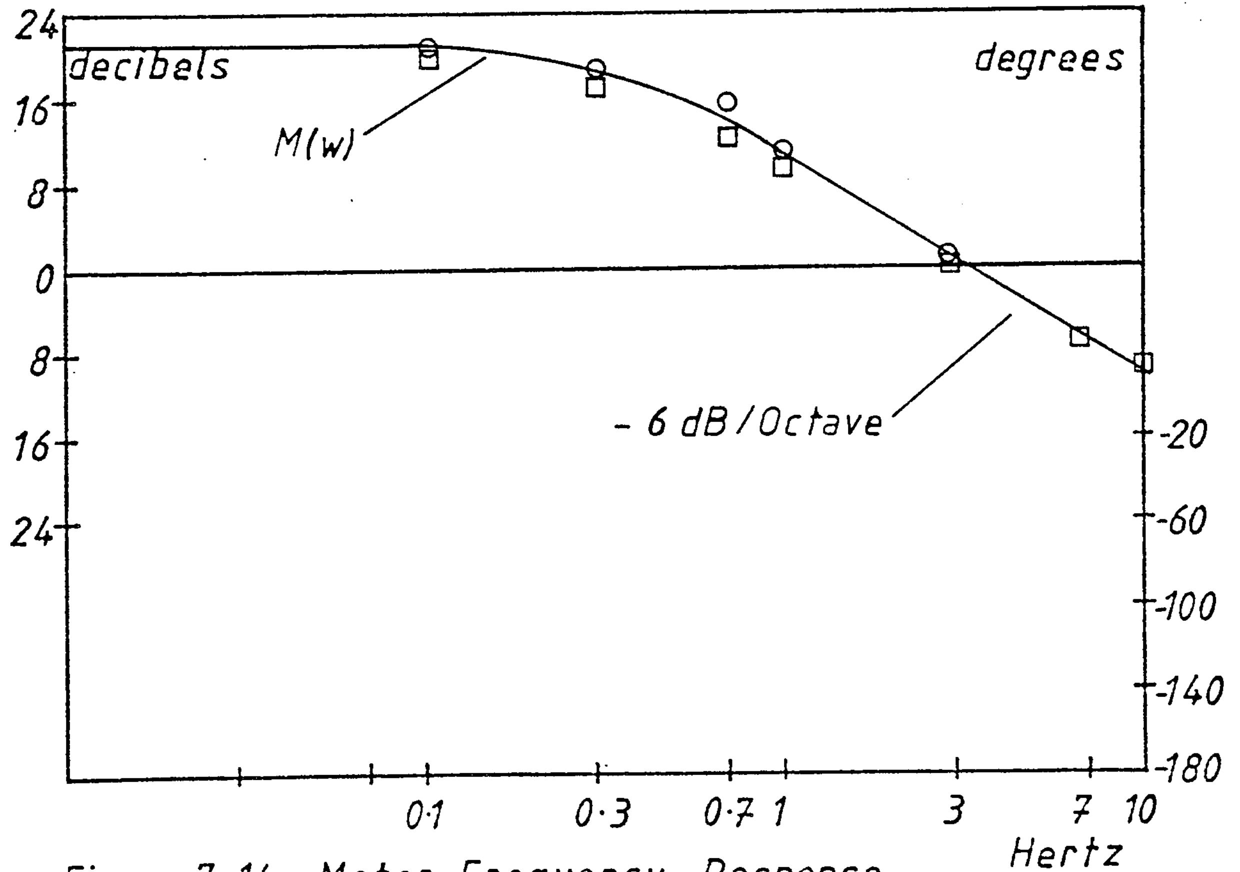


Figure 7·14 - Motor Frequency Response
Armature Volts to Speed - Half Field
○ Measured □ Theoretical

breakpoint frequency become

$$M = 20 \text{ db} \quad \text{and} \quad fb = 0.32 \text{ Hz} \tag{7.6}$$

and this agrees closely with both the measured and the model results. Thus the effect of reducing the field is to increase the d.c. gain and hence reduce the bandwidth of the motor response. The reduction in bandwidth will limit the speed of response of the motor and is thus undesirable. Accordingly the motor is always run at full field. Furthermore, a higher Bm value would increase the bandwidth and hence the system speed of response, pointing to the use of servometers which generally have high Bm values. Figure 7.15 shows the normalised responses of the NECO motor and two servomotors. The NECO motor has a Bm value of 0.14 and the two servomotors have values of 0.81 for a standard servomotor and 0.92 for a rare-earth magnet servomotor. The increase in bandwidth afforded by these motors is supplied at the expense of gain. The d.c. magnitude of the servomotors is much lower than that of the NECO motor. However, gain is a factor which can easily be made up in other parts of the system, whereas bandwidth is not.

Thus for the open loop response to speed, the theory adequately explains the motor operation, and the action of the field can be understood in terms of the effect that the motor constant Bm has on the d.c. magnitude and breakpoint frequency of the motor response.

7.3.2 Input Signal to Wheel Position - Open Loop

In measuring the open loop response to position, two major problems were encountered due to the form of the response and the nature of the friction load on the wheels. Recalling equation 5.15, the open loop response to position is

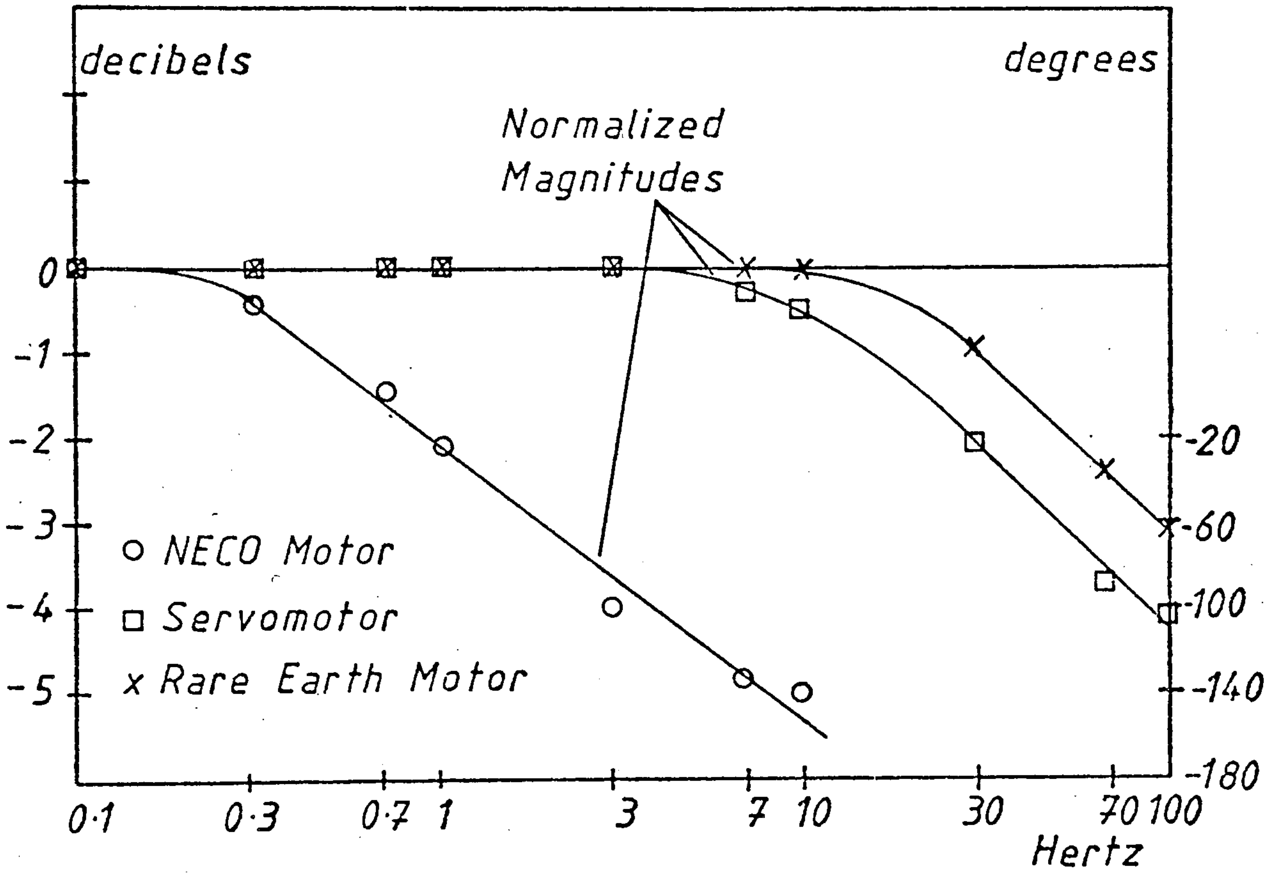


Figure 7·15 -Motor Frequency Response
Armature Volts to Speed
Comparison of Different Motor Types

$$\frac{\delta}{Vin} = \frac{G\,K_1\,K_2}{s\,(1 + s\,T_1)} \qquad \text{(5.15 repeated)}$$

The single s in the denominator means that there is an integrator in the response. This means that an input signal level which produces an adequate level of output signal at low frequencies will produce a negligibly small level of output at high frequencies. Conversely a signal level which produces an adequate level of output at high frequencies will cause an enormous output level at low frequencies. Practically the output is the turning of the wheels. If the output level goes too high the wheels will just stick at full lock, and if a lot of power is still applied this could cause damage to the steering track rods. Thus different levels of input signal must be applied, and this leads to the second problem. Since the maximum output is lock-to-lock of the steering wheels, the wheels must move at slower velocity at lower frequencies, and this is achieved by putting in a smaller signal level. However, the value of friction between the wheels and the ground alters with speed, being highest at zero speed (the stiction value) and dropping to some high speed running value (see Figure 7.16). Thus the results recorded at lower frequencies will be at a higher friction value than the results recorded at higher frequencies. This non-linearity makes it misleading to apply a linear analysis to the recorded results. Accordingly in considering the open loop response to position, results from the computer simulation only will be considered. Figure 7.17 shows the response calculated from a two variable programme, which models the open loop motor response to position. Figure 7.17 shows the response using two values of the friction coefficient Bv. The low friction value is the same as was used previously. This value was calculated from the recorded data for the Pf vs Bm curve in the following way:

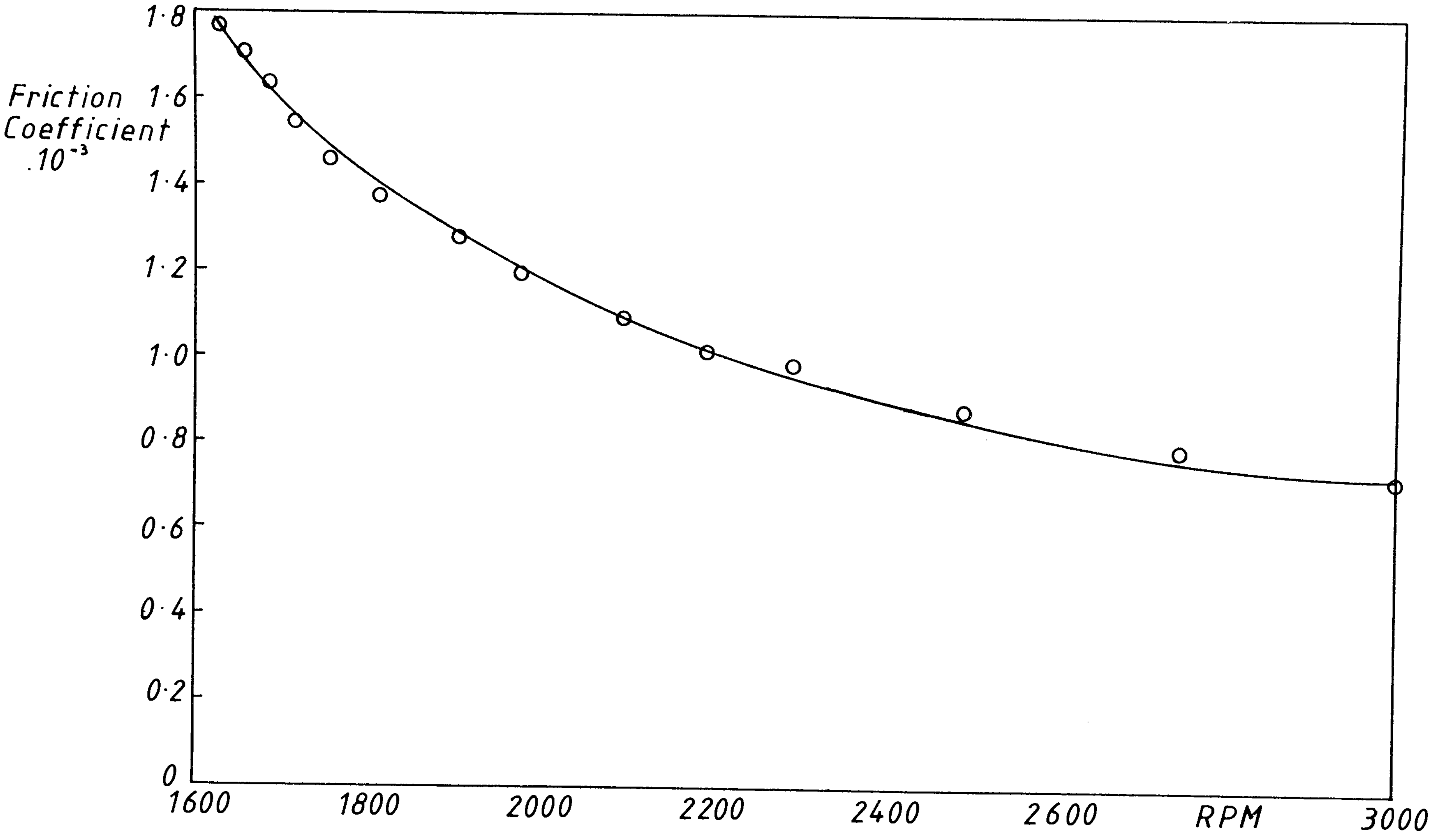


Figure 7·16 - The Friction vs. Speed Profile for the Steering Motor

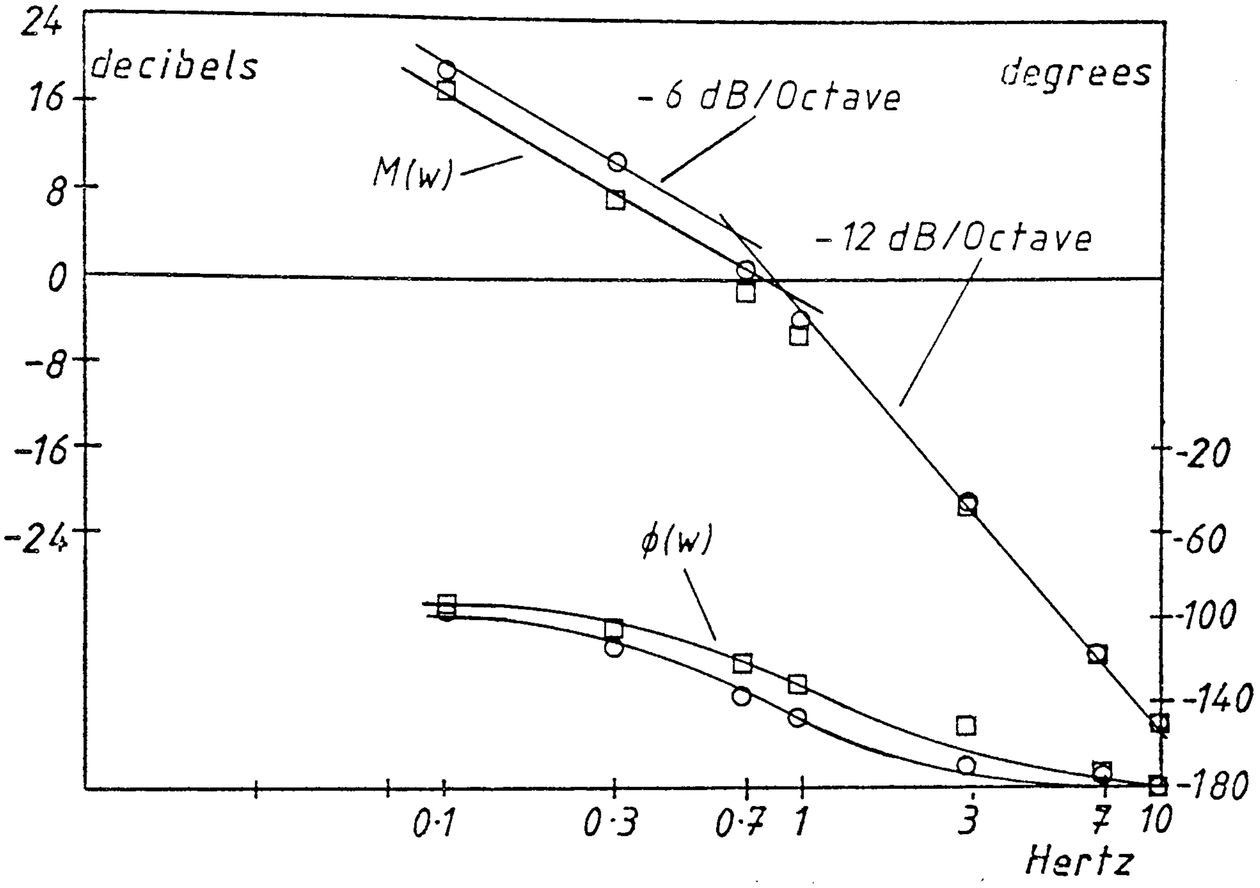


Figure 7·17 -Motor Frequency Response
Input Signal to Position - open loop
○ Low Friction □ High Friction

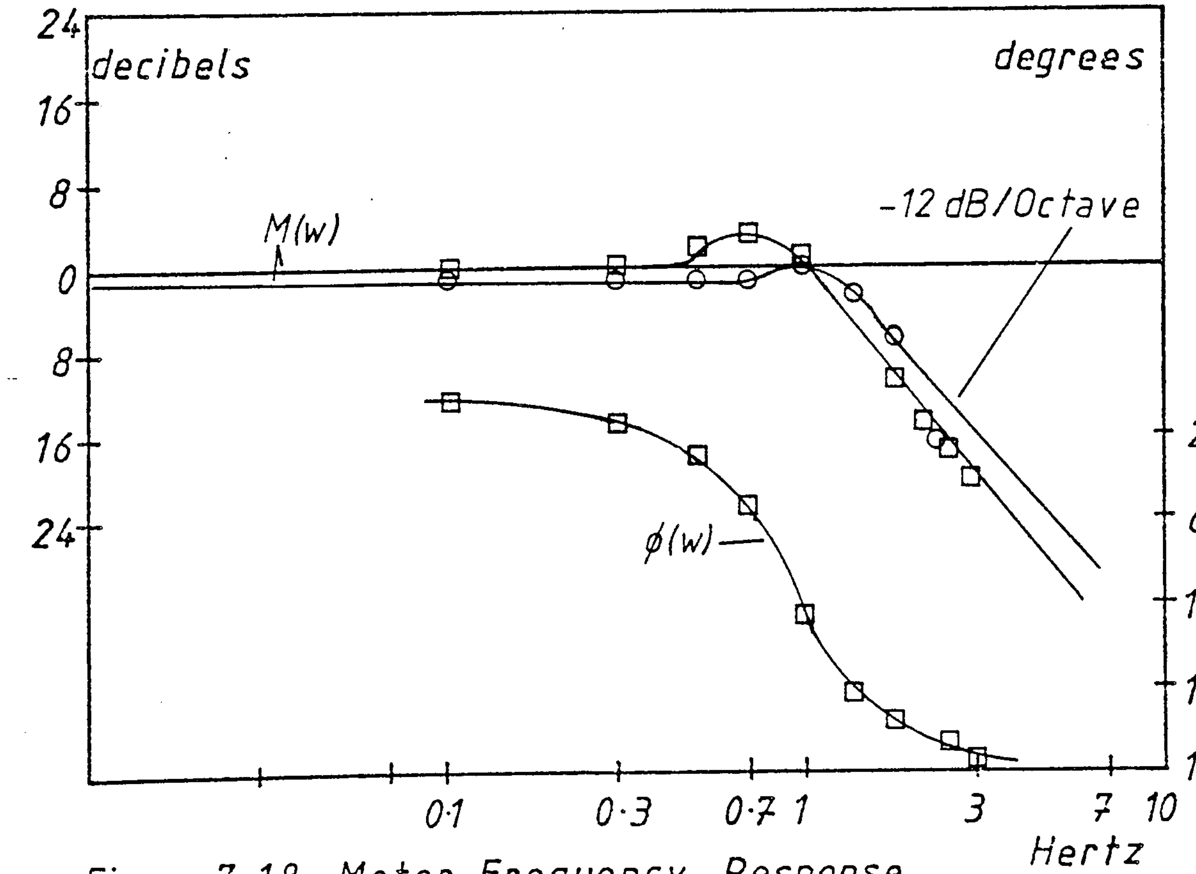


Figure 7·18- Motor Frequency Response
Input Signal to Position - closed loop
○ Measured □ Theoretical

recalling equations 5.1 and 5.5 gives

$$T = Bm . Ia \qquad (5.1 \text{ repeated})$$

and

$$T = J\alpha + Bv . w + Tq \qquad (5.5 \text{ repeated})$$

In the steady state condition, $\alpha = 0$ and neglecting Tq, the two equations can be equated to give

$$Bm \; Ia = Bv . w \qquad (7.7)$$

Knowledge of the armature current, the shaft speed and the Bm value gives the friction coefficient directly. From Figure 6.8, when the field current is 1.9A (full field) the Bm value is 0.14. From Table 7.1 the steady state values of Ia and w when the field current is 1.9A are Ia = 2.34 and w = 172.17. Thus

$$Bv = \frac{Bm \; Ia}{w} = 0.002 \qquad (7.8)$$

Although strictly speaking this is only the friction value at the steady state speed of 172.17 rad s^{-1} and thus not applicable to a transient or sinusoidally varying response, it does serve as a first approximation, and the agreement between the measured and theoretical results so far show that it is a good approximation. The Bv values calculated from the steady state data recorded for the Pf vs Bm curve are shown plotted against speed in Figure 7.16.

Referring to Figure 7.17, the higher friction value is more repesentative of this stage of the motor response and shows quite clearly the effect of an increase in friction in the system. It lowers the system gain and hence increases the bandwidth.

The lack of any measured results to validate the theory at this stage is not too serious a problem. The results for the open loop response to speed were measured with the gearbox in position and so the friction and moment of inertia values used in the simulation include the gearbox. Because of the gearbox the moment of inertia of the track rods and wheels is negligible compared with that of the armature and gearbox and so the only effect of the wheels is to increase the system friction. The response to position includes the gear ratio and a single integration and neither of these are dynamic effects. Thus the simulation results in Figure 7.17 accurately show the system open loop response to position.

7.3.3 Input Signal to Wheel Position - Closed Loop

Because of the continually increasing nature of the open loop response, due to the single s in the denominator of the transfer function (equation 5.15), the steering motor is placed in a closed loop angle demand system. This is convenient for the manual control system where the deviation of a potentiometer wiper from a central position sets an angle on the wheels and thus makes the vehicle handle like a car. But it is essential for the stability of the automatic steering system, and as Larcombe notes[9] must be present in all steering systems even if only, as is usually the case, by an unwitting feature of design. The need for the feedback of the wheel angle to ensure system stability will be proven later in Section 7.6.

Figure 7.18 shows the measured and theoretical frequency response plots for the closed loop system. The theoretical result is the output of a programme which calculates its output on the basis of the low friction value and assuming no torque losses. The failure of these two assumptions can be seen in Figure 7.18. The flat region of the measured response is approximately 1dB below the calculated level. This is due to the torque losses in the system, which reduce the system gain. Also the resonant frequency of the measured system is somewhat greater than that of the calculted system. This is because of the increased friction in the measured system due to the presence of the wheels. The increased friction also reduces the open loop gain factor K_1 (see equation 5.10) but its effect is minimal because of the closed loop system. Indeed one of the major advantages of a closed loop system is the reduction of the system sensitivity to parameter variation. Thus a sudden change in the friction coefficient, due to an oil patch for example, while altering the open loop gain, would not seriously affect the closed loop gain and the steering angle would remain unaltered.

The open loop response of the motor from input signal to shaft position is given by equation 5.15

$$\frac{\delta}{Vin} = \frac{G\,K_1\,K_2}{s\,(1 + s\,T_1)} \qquad \text{(5.15 repeated)}$$

The values of K_1 and T_1 are given in equation 7.3. The gear ratio used with the NECO motor was 1/45.6. Between the input signal and the armature lay four stages of gain. These were: the analogue-to-digital converter with a gain of 51 V^{-1}; the software multiplier of 4 in the steering programme; the gain of the PWM circuit which was 1%; and the gain of the motor driver circuit which was 0.24 V $\%^{-1}$. The gain factor K_2 is the product of all these factors, and hence

$$K_2 = 48.96 \tag{7.9}$$

giving

$$\frac{\delta}{Vin} = \frac{7.67}{s\ (1 + 0.26\ s)} \tag{7.10}$$

In the closed loop system the voltage from the wheel angle potentiometer is fed back and after being digitised is compared with the digitised Vin signal. Figure 7.19 shows the closed loop system both in its elemental form and in its equivalent form. Since both Vin and the potentiometer voltage go through the same ADC then it can be taken behind the summing junction go give the unity feedback system shown in Figure 7.19b. The closed loop response is given by equation 5.17, and filling in the values gives

$$C(s) = \frac{30.08}{s^2 + 3.92\ s + 30.08} \tag{7.11}$$

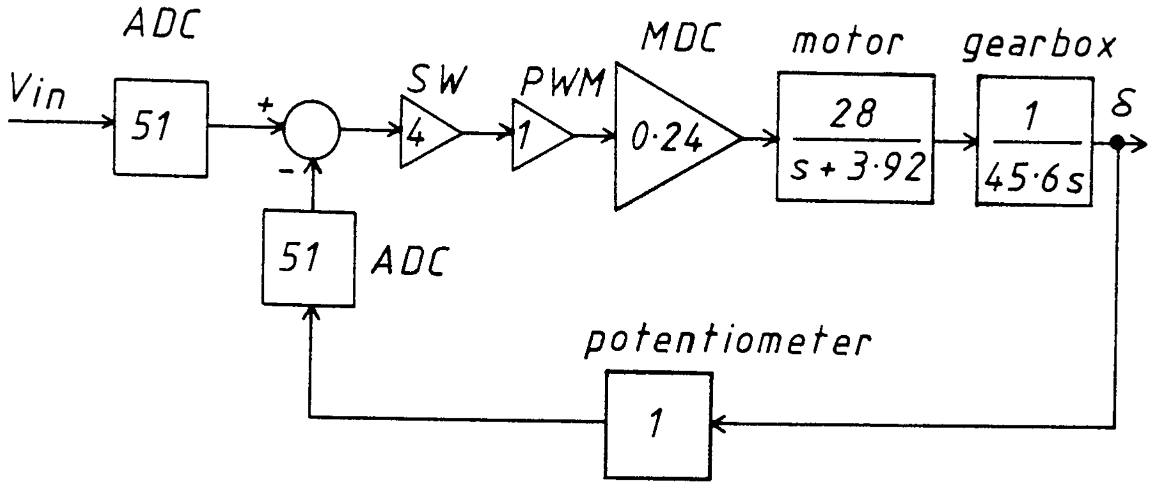
Which from equations 5.19 and 5.20 gives

$$Wn = 5.48 \text{ rad } s^{-1} \tag{7.12}$$

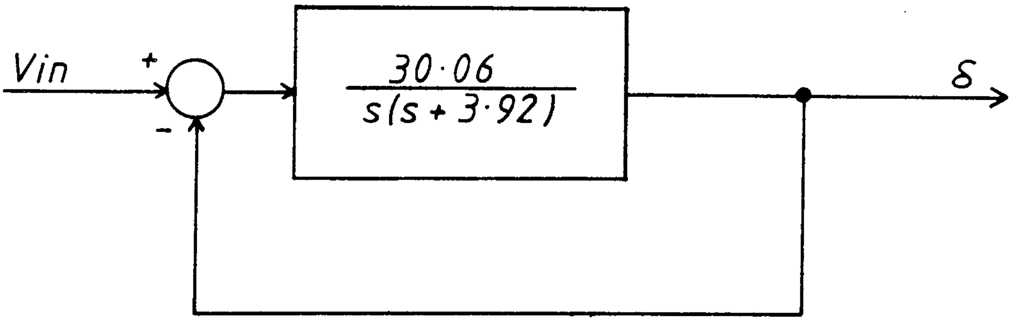
and

$$\zeta = 0.36 \tag{7.13}$$

From Figure 5.8, a damping ratio of 0.36 implies a peak magnitude Mpw of 1.5 and the ratio of resonant to natural frequency Wr/Wn of 0.86. Thus



a) Elemental Form



b) Equivalent Form

Figure 7.19 - The Closed Loop Angle Demand System Block Diagram

$$Wr = 4.71 \text{ rad s}^{-1} \tag{7.14}$$

i.e.

$$fr = 0.75 \text{ Hz} \tag{7.15}$$

where $fr = 2 \pi wr$

Referring to Figure 7.18, the measured peak magnitude is $Mpw = 1.14$ and from Figure 5.8 this implies that

$$\zeta = 0.52 \tag{7.16}$$

Also from Figure 7.18 it can be seen that

$$fr = 1 \text{ Hz} \tag{7.17}$$

A comparison of the theoretical values in equations 7.13 and 7.15, and the measured values in equations 7.16 and 7.17 shows reasonable agreement. However, it must be remembered that the theoretically generated values do not allow for the higher friction value present in the system, nor do they take into account the torque losses present in the system. Both of these will have the effect of depressing the peak magnitude and thus making the damping ratio look higher. Also by depressing the gain, this will increase the system bandwidth as can be seen in the shift between the theoretical and the measured peak.

Thus the use of a simple linearised model produces results which tie in quite well with the measured results. This is mainly due to the fact that in a closed loop system the sensitivity of the system to parameter variation and external disturbances is much reduced from the open loop case. The agreement between theoretical and measured results gives confidence to both the theory and the model of the motor and its associated control loop.

7.4 THE VEHICLE RESPONSE

The theory of the lateral response of the vehicle was covered in Section 5.3. It derived expressions for both the lateral displacement y and the measured deviation d (see Figure 5.10) of any point on the vehicle centre axis relative to a line which is the extension of the initial vehicle centre line. Thus it accurately describes the lateral movement of the vehicle relative to a straight guide wire, but is not suitable for cases where the guide wire is curved. This will be dealt with in Section 7.5. This Section will compare measured results with the results calculated from this straight wire theory.

Figure 7.20 shows a comparison of theoretical and measured lateral deviations for three different constant steering angles. The close correlation between the two sets of results gives some validation to the theory.

Figure 7.21 shows a Bode plot of the theoretical system response for a vehicle velocity of 0.5 ms^{-1}. The response is of the form

$$\frac{d}{\delta} = \frac{K_1 (s + z)}{s^2} \qquad (7.18)$$

where K_1 is a gain factor of the lateral response and z is a system zero.

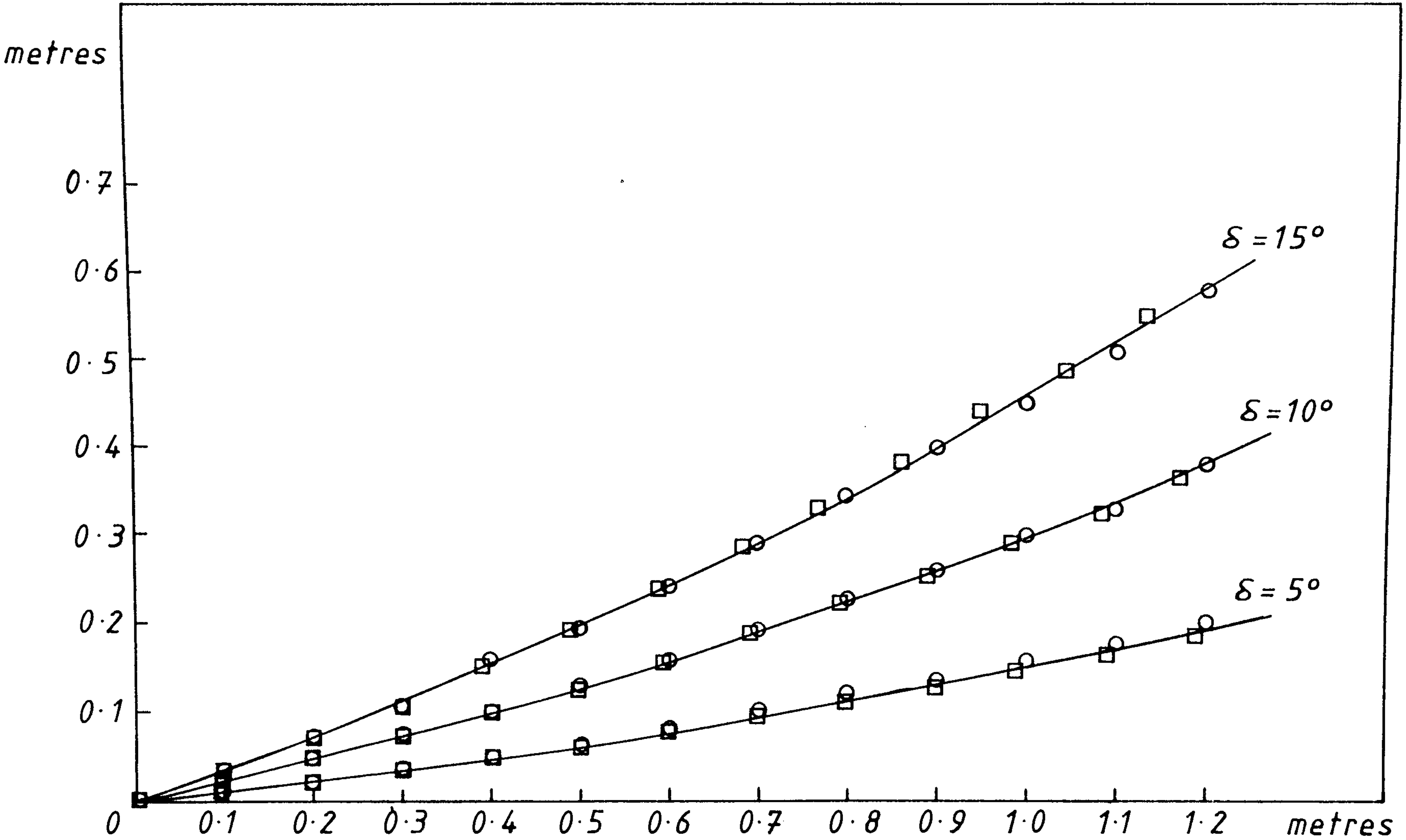


Figure 7·20 – Comparison of Vehicle Lateral Deviations for constant steering angles
○ Measured □ Theoretical

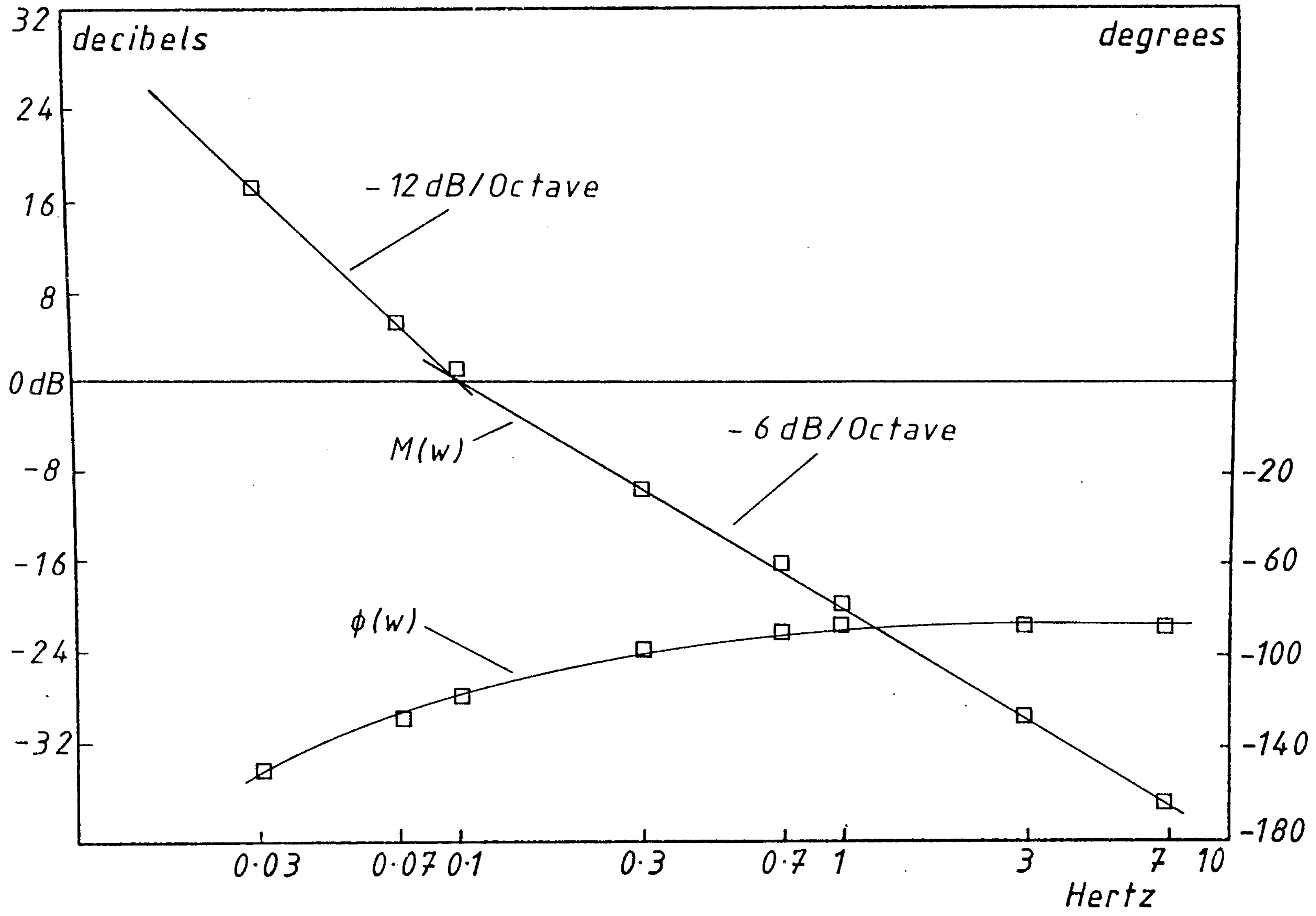


Figure 7·21 - Vehicle Lateral Response - Bode Plot for u=1·4 , Vo = 0·5

This form of the response can be derived from the theory. Recalling equations 5.29, 5.31 and 5.36

$$d = \int (U \tan \psi + V) \, . \, dt \qquad \text{(5.36 repeated)}$$

where $U = Vo$

$$V = \frac{Vo \, . \, u \tan \delta}{l} \qquad \text{(5.29 repeated)}$$

$$\psi = \int \frac{Vo \tan \delta \, . \, dt}{l} \qquad \text{(5.31 repeated)}$$

and Vo, U and l have no time dependence. Substituting in equation 5.36 for U, V and ψ, and separating the two terms gives

$$d = \int Vo \tan \left\{ \int \frac{Vo \tan \delta \, . \, dt}{l} \right\} . \, dt + \int \frac{Vo \, . \, u \tan \delta \, . \, dt}{l} \qquad (7.19)$$

This expression is not linear due to the tangent functions. Its response is given accurately in the programmes since these use the full algebraic form of the equation. However, for the sake of a linear analysis which will provide some feel for the way the system behaves, it will be assumed that all angles are small enough for the tangent of the angle to be approximated by its argument. In practice, this is a reasonable assumption when the vehicle is travelling along a straight wire since it never deviates far from the wire and so any steering angle δ applied is small, and the vehicle attitude to the wire ψ remains correspondingly small too. Thus equation 7.19 becomes

$$d = \int Vo \left\{ \int \frac{Vo \, \delta}{l} \, . \, dt \right\} . \, dt + \int \frac{Vo \, . \, u \, . \, \delta}{l} \, . \, dt$$

$$= \frac{Vo^2}{l} \int \int \delta \; . \; dt \; . \; dt + \frac{Vo.u}{l} \int \delta \; . \; dt \tag{7.20}$$

Now the Laplace transform of an integral is given by [57]

$$L \left(\int_{0^+}^{\infty} f\,(t) \; . \; dt \right) = \frac{L\,(f)}{s} + \frac{f\,(0^+)}{s}$$

$$= \frac{F\,(s)}{s} + \frac{f\,(0^+)}{s} \tag{7.21}$$

where L denotes the Laplace transform

$f(t)$ is the time function

and $f(0^+)$ is the value of $f(t)$ at the time $t = 0$

Thus

$$L \left(\int \int f\,(t) \; . \; dt \; . \; dt \right) = \frac{L\,(\int f\,(t) \; . \; dt)}{s} + \frac{\int f\,(0^+) \; . \; dt}{s}$$

$$= \frac{\left\{ \frac{L\,(f(t))}{s} + \frac{f\,(0^+)}{s} \right\}}{s} + \frac{\int f\,(0^+) \; . \; dt}{s}$$

$$= \frac{F\,(s)}{s^2} + \frac{f\,(0^+)}{s^2} + \frac{\int f\,(0^+) \; . \; dt}{s} \tag{7.22}$$

Taking the Laplace transform of equation 7.20

$$D(s) = \frac{Vo^2}{l} \left\{ \frac{\Delta(s)}{s^2} + \frac{\delta(0^+)}{s^2} + \frac{\int \delta(0^+).dt}{s} \right\} + \frac{Vo.u}{l} \left\{ \frac{\Delta(s)}{s} + \frac{\delta(0^+)}{s} \right\} \tag{7.23}$$

$$= \Delta(s) \left\{ \frac{Vo^2}{s^2 l} + \frac{Vo.u}{sl} \right\} + \delta(0^+) \left\{ \frac{Vo^2}{s^2 l} + \frac{Vo.u}{sl} \right\} + \int \delta \; (0^+).dt.\frac{Vo^2}{sl} \tag{7.24}$$

where $D(s)$ is the Laplace transform of $d(t)$

$\Delta(s)$ is the Laplace transform of $\delta(t)$

and $\delta(0^+)$ is the initial value of $\delta(t)$

The transfer function of a linear system is defined as the ratio of the Laplace transform of the output variable to the Laplace transform of the input variable, with all initial conditions assumed to be zero[46], i.e.

$$\delta(0^+) = 0 \qquad (7.25)$$

and hence $\int \delta\ (0^+)\ .\ dt = 0$ (7.26)

Thus equation 7.24 becomes

$$D(s) = \Delta(s)\ \{ \frac{Vo^2}{s^2 1} + \frac{Vo.u}{s1} \} \qquad (7.27)$$

and the transfer function of the linearised vehicle lateral response is given by

$$\frac{D(s)}{\Delta(s)} = \frac{Vo^2}{s^2 1} + \frac{Vo.u}{s1} = \frac{Vo.u}{1} \{\frac{s + Vo/u}{s^2}\} \qquad (7.28)$$

Equating expressions 7.18 and 7.28 gives

$$K_1 = \frac{Vo.u}{1} \quad \text{and} \quad z = \frac{Vo}{u} \qquad (7.29)$$

Figure 7.22 shows the magnitude information only of the frequency response plots of the measured deviation d of the point u = 1.4 for three different vehicle velocities. The effect of velocity on the gain and the system zero can be seen quite clearly. Increasing the velocity both increases the gain factor K_1 and increases the frequency of the zero in accordance with equation 7.29. Table 7.4 shows the values of K_1 and z at different velocities both from the exact calculation as measured from the plots in Figure 7.22 and from the approximate linearised calculation from equation 7.29. The

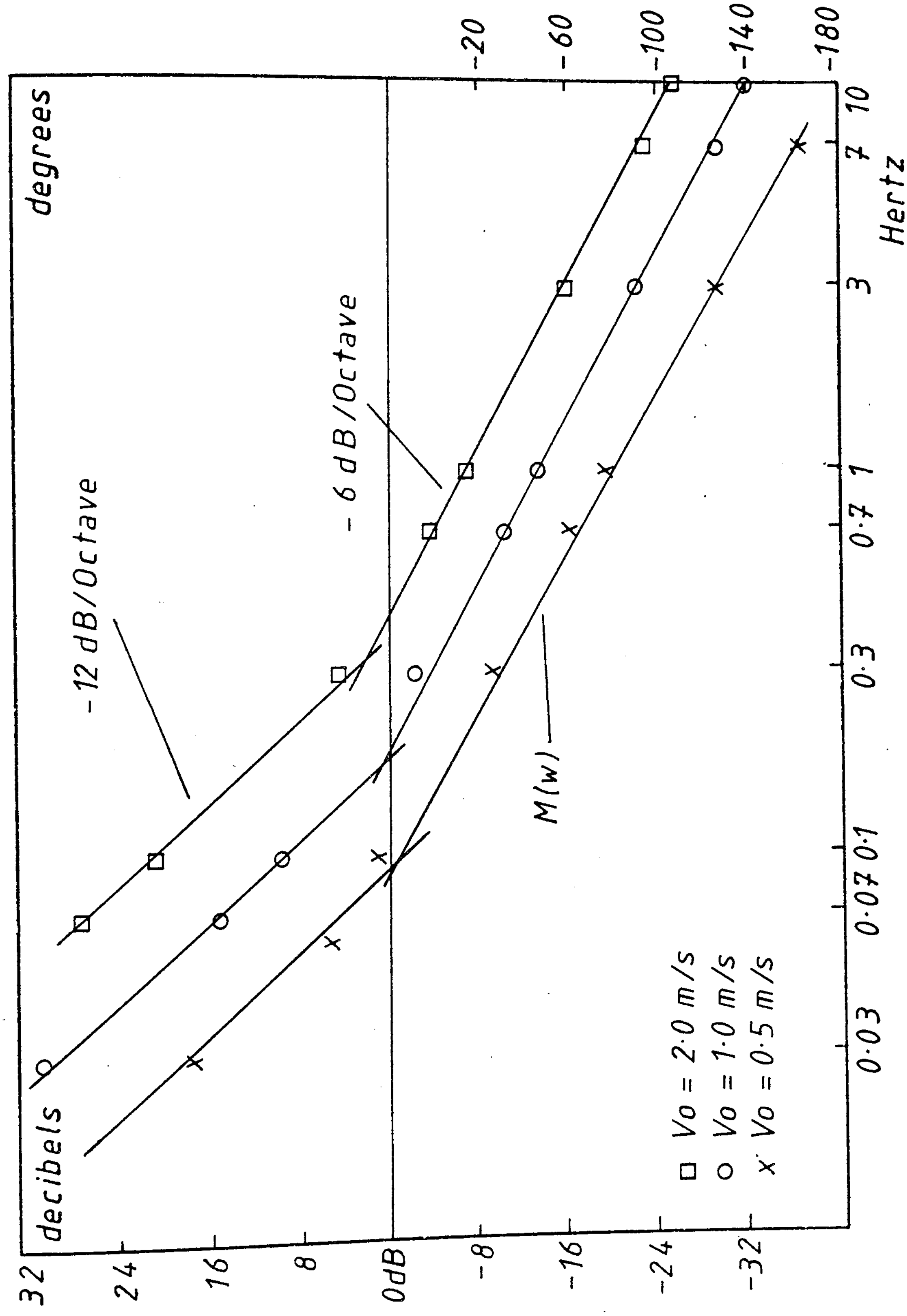


Figure 7·22 - Vehicle Lateral Response showing the Effect of Velocity

V_o	EXACT CALCULATION		APPROXIMATE CALCULATION	
	K_1	z	K_1	z
0.5	0.38	0.09	0.61	0.06
1.0	1.32	0.16	1.22	0.11
2.0	4.79	0.31	2.43	0.23

TABLE 7.4: COMPARISON OF APPROXIMATE AND EXACT CALCULATIONS OF K_1 AND z FOR THE POINT $u = 1.4$

approximation is seen to break down for higher velocities. This is because the vehicle attitude to the wire is increased and so the small angle approximation loses its validity. However, the approximation is valid for small values of Vo and δ, and provides a good qualitative feel for the response of the vehicle. This response will now be considered in greater detail.

Equation 7.19 shows that there are two terms to the vehicle lateral response. The first term is due to the vehicle attitude and the second term is due to the initial angle that the velocity vector of a point on the vehicle has to the wire. Referring to Figure 5.10 this is the angle α for the point P. At the back axle, this angle is zero and by putting $u = 0$ in equation 7.19, the second term disappears. Thus the lateral deviation of the back axle is due to the change in attitude alone. Equation 7.27 shows that the response for this point is given by

$$\frac{D(s)}{\Delta(s)} = \frac{Vo^2/l}{s^2} \tag{7.30}$$

This gives a constant - 12 dB/Octave slope at a phase angle of -180^o on the Bode plot and would be unstable if connected up in a closed loop system. Thus the lateral position sensor cannot be located at the back axle, but must be displaced some distance from it. The effect of this displacement is to introduce a zero which from equation 7.18 and 7.29 is at the point

$$s = -z = -\frac{Vo}{u} \tag{7.31}$$

If the sensor is located behind the back axle then u is negative and the zero is located in the right hand position of the s-plane. This means that for velocities greater than zero a section of the steering system root locus plot will always be in the right hand s-plane and result in an unstable system. If, however, the sensor is located forward of the back axle, then the zero is in the left hand s-plane and the steering system remains conditionally stable. The stability of the system will be considered in more detail in Section 7.6.

Thus the effect of displacing the lateral position sensor from the back axle introduces a zero into the vehicle lateral response, and if the sensor is placed forward of the back axle then this zero will have a stabilising effect on the system. It does this by increasing the phase margin of the system. Referring to Figure 7.21 it can be seen that where the magnitude response crosses the 0dB line, the phase has been lifted above -180^{o} by the zero. The amount of lift provided will depend upon the position of the zero. The lower in frequency the zero is, the more phase advance it provides at the crossover point. Equation 7.29 shows that the position of the zero depends upon the vehicle speed Vo and the position of the sensor u. Thus moving the sensor forward will increase u and decrease z. This will provide more phase advance at the crossover point and thus acts as a stabilising effect, a fact already noted by Larcombe[9]. Conversely, increasing the vehicle speed will make the system less stable by increasing the position of the zero. In the complete steering system there are also the effects of the angle demand system and the sensor to consider. The sensor is a pure gain factor, and by raising the whole response curve will increase the gain margin. Since the crossover point is always well below the resonant frequency of the angle demand system, the gain factor of this system is 0dB, and does not alter the magnitude response. However, there will be some phase lag and this will reduce the phase margin. Furthermore, as the vehicle speed increases and the position of the crossover point moves up in frequency, then the amount of phase lag due to the angle demand system increases and tends to make the complete system less stable. Thus increasing the vehicle speed reduces the phase margin by two effects: firstly, due to the increase in the position of the zero in the vehicle lateral response and secondly, due to the increase in phase lag of the angle demand system with frequency.

The gain factor K_1 depends upon Vo, u and l. Increasing the vehicle speed simply increases the lateral displacement of all points, and hence the zero. The further forward from the rear axle a point is the further it will move away from the wire and this is reflected by the presence of u in the gain factor. The denominator of the gain factor is the vehicle wheelbase l. This means that vehicles with shorter wheelbases can react much quicker than long wheelbase vehicles.

Practically the measurement of the vehicle lateral response presents great difficulty. As noted in Section 7.3 the presence of a single integrator leads to an enormous variation in output signal over two decades. In this case the problem is exacerbated by the presence of a double integrator below the breakpoint. To measure the response the vehicle was fitted with a transversely mounted wheel at the front, which would rotate only with lateral movements of the vehicle. A potentiometer was fitted to the axle of this wheel. The closed loop angle demand system was then given sinusoidal inputs at various frequencies, and both the input voltage and the potentiometer voltage were recorded. The potentiometer voltage is directly proportional to the measured deviation d and in the region up to 1 Hz, the input signal is equal to the angle on the wheels (neglecting system torque losses). The vehicle was run at a speed of 0.1 ms^{-1} so as to minimise the lateral deviation and hence avoid hitting the end stops of the potentiometer at low frequencies. The measured response is shown in Figure 7.23 where it is compared with the theoretical response. Below 0.1 Hz, the effect of the single integrator made the response so large that the potentiometer hit its end stops and so no useful data was recorded. This means that the measured data does not show the breakpoint. However, since the breakpoint involves the response changing to a double integration, and since due to the low vehicle velocity the breakpoint is at a very low frequency anyway ($\cong$ 0.01 Hz) it is certain that the vehicle would have gone beyond the point where the vehicle attitude is 90 degrees. At this point the measured deviation d is infinite (see equation 5.31 for $\psi = 90^{o}$) and the measured potentiometer voltage would be meaningless. Thus although the theory explains what happens at large values of vehicle attitude, the deviation d is not a suitable parameter for measurement (the measurement of infinity presenting some problems!), and so this method of validating the theory is only adequate for values of vehicle attitude below 90 degrees.

Above the frequency of 1 Hz the - 12 dB/Octave slope of the closed loop angle demand system begins to take effect. This not only means that the results are not due to the lateral response of the

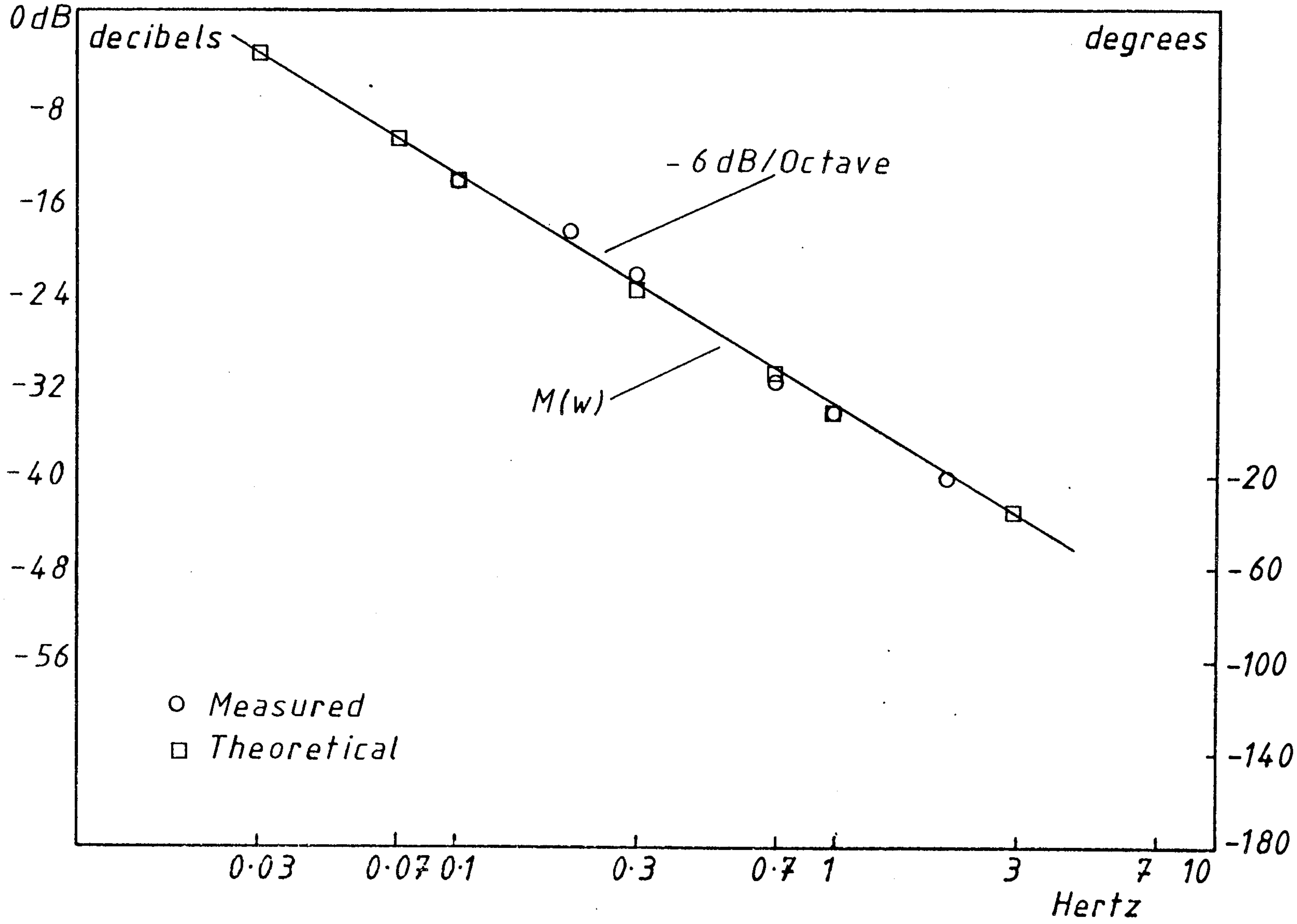


Figure 7·23 - Vehicle Lateral Response - Bode Plot for $u = 1\cdot4$, $V_o = 0\cdot1$

vehicle alone (a fact which could be compensated for) but also means that the response slope is now - 18 dB/Octave and the results become too small to be measured accurately. Thus the measured response is limited to the range of frequencies from 0.1 Hz to 1 Hz. Within this range it shows a - 6 dB/Octave slope and the theoretical results fit in well with the measured results, thus giving confidence in the theoretical analysis.

7.5 THE MOTOR - VEHICLE STEERING SYSTEM

Thus far, two major elements in the steering system have been identified. These are the steering motor and the lateral response of the vehicle. Both these elements have been analysed theoretically and measured practically and a comparison of the measured and calculated data for both elements has shown good agreement. In the complete steering system these two elements are linked together and so any analysis of the vehicle steering system must include the joining of these two elements in a single integrated steering system.

Before this can be done, however, the vehicle response analysis must be extended to allow for curves in the wire since operationally the vehicle will encounter both straight sections and curved sections of the guide wire. Figure 7.24 shows the path taken by the vehicle when an angle is put on its steering wheels. Relative to an initial datum, the deviation d_1 can be calculated according to equation 5.36. This is the theory as previously developed and can be shown in block diagram form as in Figure 7.25.

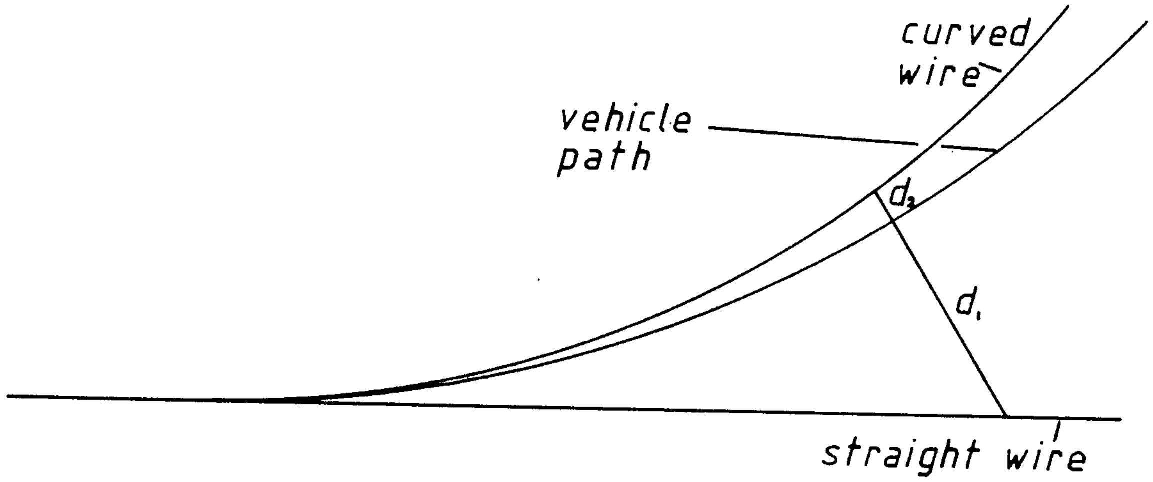


Figure 7.24 - The Effect of Wire Curvature on the Measured Deviation

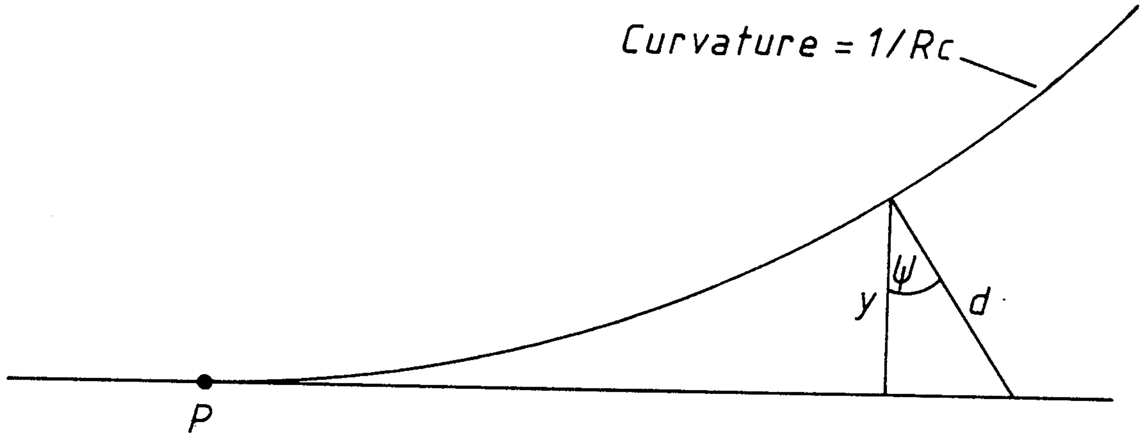


Figure 7.26 - Vehicle & Curved Wire Paths

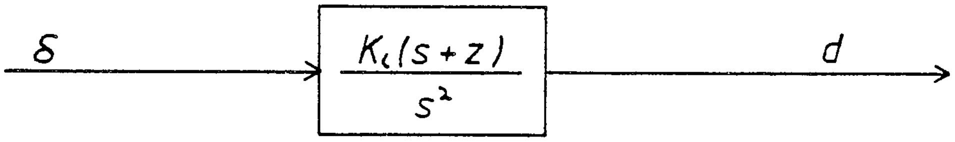


FIGURE 7.25: THE VEHICLE LATERAL RESPONSE. BLOCK DIAGRAM OF THE STRAIGHT WIRE MODEL

However, if as the angle was set on the wheels the vehicle met a curve in the guide wire, then the deviation measured by the sensor would be different. As shown in Figure 7.24 the measured deviation is now d_2 not d_1.

The reason that the model gives the wrong deviation is that it has been developed on a world coordinate basis. Thus the results would be consistent with the deviation from say a wall in the warehouse which never moves relative to the rest of the world. Then all velocities, displacements and angles of attitude are due to the vehicle alone. However, the lateral position sensor does not measure this. It is concerned simply with the instantaneous position of the wire within its sensor window. Thus the coordinate system used must be a vehicle coordinate system and the system origin would most naturally be placed at the centre of the coil assembly, where all deviations of the wire are measured from. Now relative to this new origin the object of interest (the wire) does have velocities and displacements (due to wire curvature) and so the model must be adjusted to take into account these non-vehicle velocities and displacements.

This will be done with reference to Figure 7.26 where the vehicle moves along the straight line and at the point P the wire bends on the arc of a circle of curvature 1/Rc, where Rc is the radius of the circle. The situation is similar to that given in Figure 5.10 where the vehicle followed a curved track and the wire was straight, and the mathematics for the distance y, which is now the measured deviation, is exactly the same Thus y is given by equation 5.32 where δ is replaced by δw , an equivalent "wire steering angle". To find a value for δw, it is noted in Figure 7.26 that if the wire went along the straight line and the vehicle had an angle δv applied to its wheels then the vehicle would follow the curved track. The measured deviation is now d given by

$$d = \frac{y}{\cos \psi} \qquad \text{(5.34 repeated)}$$

In cases where the attitude of the vehicle to the wire is small, then the cosine of the angle is approximately one, and d = y. Thus for small angles of attitude, the two situations are exactly the same, and whether the wire describes a curve, or the vehicle has an angle set on its wheels is immaterial to the measured deviation. This is consistent with the placing of the coordinate origin at the centre of the coil assembly. Now at the point P, irrespective of whether the wire curves or an angle is set on the wheels, the sensor "sees" the wire move laterally in its sensor window. Referring to Figure 5.10 if an angle δv is set on the wheels, then the radius of curvature of the back axle is given by equation 5.25

$$Ro = \frac{1}{\tan \delta v} \qquad \text{(5.25 repeated)}$$

i.e.

$$\delta v = \tan^{-1}\left(\frac{l}{Ro}\right) \tag{7.32}$$

Assuming that when the vehicle follows a curve in the wire, the lateral offset required at the sensor is such that the back axle of the vehicle has the same radius of curvature as the wire, then the equivalent "wire steering angle" δw can be found by substituting Rc for Ro in equation 7.32.

Thus the measured deviation now depends not only on the steering angle set on the wheels, but also on the equivalent steering angle set on the wire. This is shown in block diagram form in Figure 7.27.

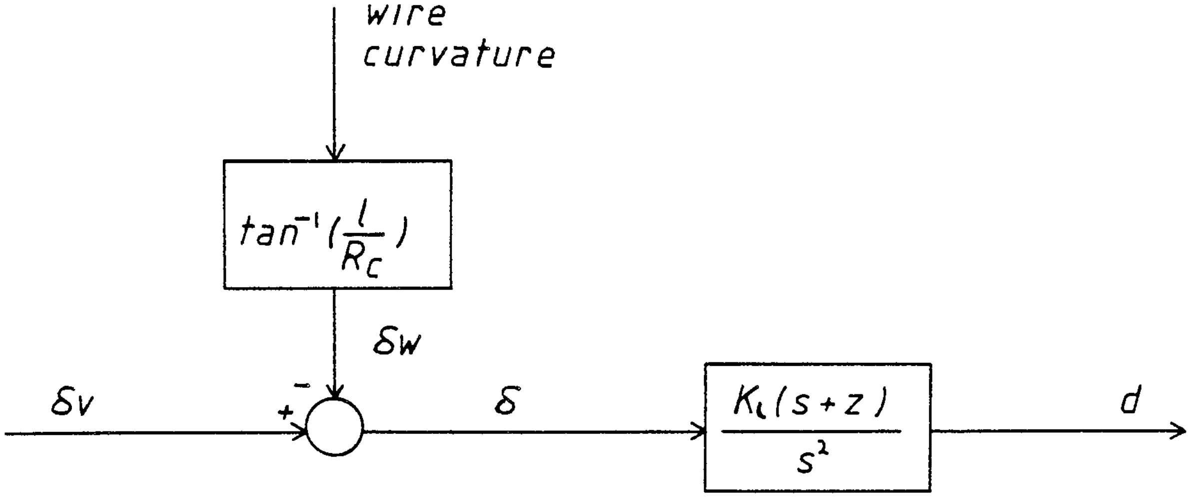


FIGURE 7.27 THE VEHICLE LATERAL RESPONSE. BLOCK DIAGRAM OF THE CURVED WIRE MODEL

The system block diagram as given in Figure 4.6 must now be altered accordingly and so the block diagram representation of the steering system is given in Figure 7.28.

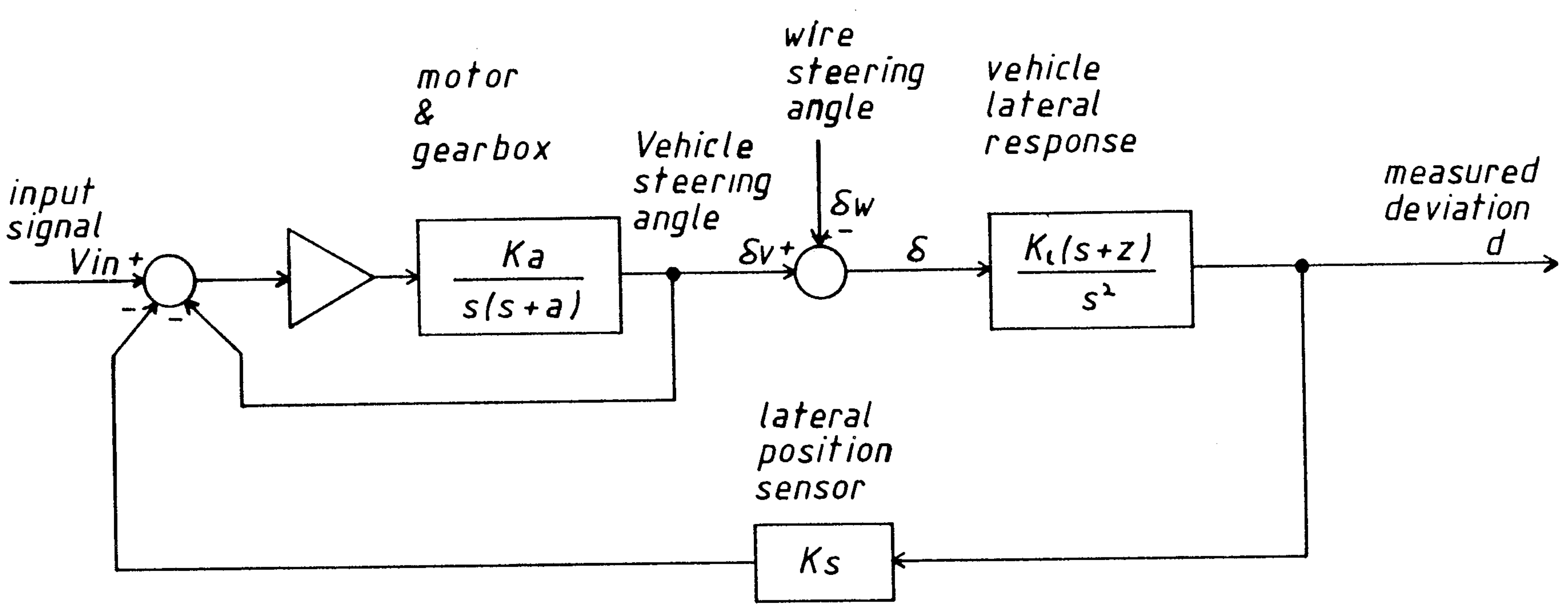


Figure 7·28 – The Complete Steering System – Block Diagram

To allow for the introduction of wire curvature, the system equations must be altered. This is done by noting that the system state variable x_2 is the vehicle steering angle δv, previously written as just δ. This must now be altered by the effect of wire curvature. Choosing the equivalent wire steering angle δw as the input signal u_3, equations 5.82 and 5.84 become

$$x_3 (k + 1) = \psi_5 \tan [x_2 (k) - u_3 (k)] + x_3 (k) \qquad (7.33)$$

and

$$x_4 (k + 1) = \psi_6 \tan [x_2 (k) - u_3 (k)] + \psi_7 \tan x_3(k) + x_4(k) \qquad (7.34)$$

A programme has been written to implement these two equations and simulate the system behaviour when the vehicle meets a curve in the wire of radius 2.3 m. The closed loop angle demand system is represented by a gain factor of 1. This approximate form is accurate below a frequency of 1 Hz, as shown by Figure 7.18. Table 7.5 shows the output from this programme. It shows the steady angle set on the wheels and the steady state error d which produces the voltage to provide this angle.

The full form of the system simulation is given by including equations 5.89 and 5.74 which provide the state space form of the equations for the motor response. This is done in a programme which also includes the higher friction value. Table 7.6 shows its output. It shows the steady angle set on the wheels and a slightly reduced steady state error d. It shows a slight oscillation before reaching the steady state angle which is not evident in practice. This is because a single value has been used for a friction coefficient whose value changes with time.

```
Ok
RUN



Vehicle response on meeting a semicircular
curve in the wire of radius  2.3 metres
At a speed of .5 metres per sec.
For the point u= 1.4


      Dw          Dv          y      Time        Att.

     26.57        28       -.093       1        -2.942

     26.57        28       -.095       2        -2.122

     26.57        28       -.093       3        -1.417

     26.57        27       -.092       4        -.94

     26.57        27       -.091       5        -.624

     26.57        27       -.09        6        -.414

     26.57        27       -.089       7        -.274

     26.57        27       -.089       8        -.182

     26.57        27       -.089       9        -.121

     26.57        27       -.089      10        -.08

     26.57        27       -.089      11        -.053

     26.57        27       -.089      12        -.035

     26.57        27       -.089      13        -.023

     26.57        27       -.089      14        -.015

     0             2       -7E-03     15         2.917

     0            -2        7E-03     16         2.462

     0            -2        5E-03     17         1.664

     0            -1        3E-03     18         1.105

     0            -1        2E-03     19         .733

     0             0        2E-03     20         .486



Table 7.5 - Vehicle Response on meeting a curved wire
             -1                  VO=0.5 m/s

Ok
```

```
Ok
RUN


Vehicle response on meeting a semicircular
curve in the wire of radius  2.3 metres
At a speed of .5 metres per sec.
For the point u= 1.4

     Dw          Dv          y       Time        Att.

   26.57         39       -.065      1          -1.607

   26.57         32       -.093      2          -2.19

   26.57         24       -.078      3          -1.176

   26.57         26       -.069      4          -.453

   26.57         28       -.074      5          -.431

   26.57         27       -.076      6          -.389

   26.57         26       -.073      7          -.211

   26.57         27       -.073      8          -.114

   26.57         27       -.073      9          -.095

   26.57         27       -.073      10         -.072

   26.57         27       -.073      11         -.041

   26.57         27       -.073      12         -.026

   26.57         27       -.073      13         -.02

   26.57         27       -.073      14         -.014

   0            -15        .035      15          3.635

   0             5         .026      16          2.648

   0             9        -9E-03     17          .742

   0            -2        -.016      18          .034

   0            -8         1E-03     19          .454

   0            -4         .014      20          .888
```

Table 7.6 - Vehicle Response on meeting a curved wire
-2 VO=0.5 m/s

```
Ok
```

Both these programmes operate on the equations 7.33 and 7.34 for the vehicle lateral response. This non-linear form of the system equations cannot be simplified further without making the small angle approximation for the vehicle attitude ψ and the system parameter δ . However, the closed loop nature of the control system works to keep the difference between the wire steering angle and the vehicle steering angle as small as possible. Also looking at Tables 7.5 and 7.6 shows that $\delta v - \delta w$ and the vehicle attitude are rarely above 10 degrees and so the small angle approximation is, in operation, quite valid. Thus the two tangent functions can be replaced by their arguments and equations 7.33 and 7.34 become

$$x_3 \ (k + 1) = \psi_5 \, x_2 \ (k) + x_3 \ (k) + T \, B_3 \, u_3 \ (k) \qquad (7.35)$$

where $B_3 = \dfrac{-\psi_5}{T} = \dfrac{-Vo}{1}$

and

$$x_4 \ (k + 1) = \psi_6 \, x_2 \ (k) + \psi_7 \, x_3 \ (k) + x_4 \ (k) + T \, B_4 \, u_3 \ (k) \qquad (7.36)$$

where $B_4 = \dfrac{-\psi_6}{T} = \dfrac{-Vo.u}{1}$

This linearised form allows the four system equations to be written in matrix form as

$$\underline{x} \ (k + 1) = \underline{\psi} \, \underline{x} \ (k) + T \, \underline{B} \, \underline{u} \ (k) \qquad (7.37)$$

$$\text{where} \quad \underline{x} = \begin{matrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{matrix} = \begin{bmatrix} w \\ \delta v \\ \psi \\ d \end{bmatrix} \qquad (7.37.1)$$

$$\psi = \begin{bmatrix} \psi_1 & \psi_2 & 0 & \psi_3 \\ \psi_4 & 1 & 0 & 0 \\ 0 & \psi_5 & 1 & 0 \\ 0 & \psi_6 & \psi_7 & 1 \end{bmatrix} \tag{7.37.2}$$

$$\underline{u} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} Vin \\ Tq \\ \delta w \end{bmatrix} \tag{7.37.3}$$

and

$$\underline{B} = \begin{bmatrix} B_1 & B_2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & B_3 \\ 0 & 0 & B_4 \end{bmatrix} \tag{7.37.4}$$

A programme was written to implement this linear form of the system matrix equation. Its output is shown in Table 7.7 and as can be seen the small angle approximation does not affect the accuracy of the results. Thus the simulation provided by equation 7.37 is an accurate representation of the complete motor-vehicle system.

7.6 THE SYSTEM STABILITY

The complete system block diagram is shown in Figure 7.28. If the wheel angle feedback is omitted, then the transfer function of

```
Ok
RUN


Vehicle response on meeting a semicircular
curve in the wire of radius  2.3 metres
At a speed of .5 metres per sec.
For the point u= 1.4

   Dw        Dv        y      Time        Att.

  26.57      39      -.068     1         -1.779

  26.57      31      -.093     2         -2.171

  26.57      24      -.077     3         -1.132

  26.57      26      -.069     4         -.472

  26.57      28      -.074     5         -.449

  26.57      27      -.075     6         -.385

  26.57      26      -.073     7         -.208

  26.57      27      -.073     8         -.117

  26.57      27      -.073     9         -.097

  26.57      27      -.073     10        -.071

  26.57      27      -.073     11        -.041

  26.57      27      -.073     12        -.026

  26.57      27      -.073     13        -.02

  26.57      27      -.073     14        -.014

  0         -12       .038     15         3.824

  0          7        .019     16         2.435

  0          7       -.012     17         .621

  0         -4       -.014     18         .136

  0         -8        4E-03    19         .596

  0         -2        .015     20         .915


Table 7.7 - Vehicle Response on meeting a curved wire
           - 3                 VO=0.5 m/s

Ok
```

the motor section is given by equation 5.15, i.e.

$$\frac{\delta}{\mathrm{Vin}} = \frac{G\,K_1\,K_2}{s\,(1 + s\,T_1)} \qquad (5.15\ \text{repeated})$$

With the initial conditions zero, the open loop transfer function is

$$GH(s) = \frac{Ka}{s\,(1 + s\,T_1)} \cdot \frac{K_1\,(s + z)\,.\,Ks}{s^2} \qquad (7.38)$$

where G(s) is the transfer function of the forward path

H(s) is the transfer function of the feedback path

and $Ka = GK_1\,K_2$

The characteristic equation q(s) of the closed loop system is given by[46]

$$q(s) = 1 + GH(s) \qquad (7.39)$$

i.e.

$$q(s) = s^4\,T_1 + s^3 + s\,.\,Ka\,Ks\,K_1 + Ka\,Ks\,K_1\,z \qquad (7.40)$$

One of the necessary conditions for stability is that the characteristic equation has all non-zero coefficients[46]. Thus the absence of the coefficient of s^2 shows that without wheel angle feedback the system is unstable, a fact previously reported.

If the wheel angle feedback is now included, the transfer function of the motor section is given by equation 5.17, i.e.

$$\frac{\delta}{\mathrm{Vin}} = \frac{Ka}{s^2 + as + Ka} \qquad (5.17\ \text{repeated})$$

Thus the open loop transfer function becomes

$$GH(s) = \frac{Ka}{s^2 + as + Ka} \cdot \frac{K_1 (s + z) \cdot Ks}{s^2} \qquad (7.41)$$

and the characteristic equation of the closed loop system is

$$q(s) = s^4 + s^3 a + s^2 Ka + s\, Ka\, K_1\, Ks + Ka\, K_1\, Ks\, z \qquad (7.42)$$

To investigate the absolute stability of this system, the Routh-Hurwitz criterion is applied to the characteristic equation. Details about the Routh-Hurwitz criterion and the calculations required to establish the Routh-Hurwitz array from equation 7.42 are given in Appendix B. Putting in the values for the various constants and substituting for K_1 and z from equation 7.29, the evaluated array, as given in the Appendix is

$$\begin{array}{c|ccc}
S^4 & 1 & 30 & 156\ Vo^2 \\
S^3 & 3.92 & 220\ Vo & 0 \\
S^2 & 30\ (1 - 2\ Vo) & 156\ Vo^2 & 0 \\
S^1 & 220\ Vo & 0 & 0 \\
S^0 & 156\ Vo^2 & 0 & 0
\end{array}$$

The Routh-Hurwitz criterion states that the number of roots of the characteristic equation q(s) with positive real parts, is equal to the number of changes in sign of the first column of the array. Since roots with positive real parts represent an unstable system, then for stability there must be no changes in sign in the first column of the array. For the array above, the first two values of the first column are both positive, and so all the values in the first column must be positive. This requires that

$$1 - 2 Vo > 0 \tag{7.43}$$

$$220 \quad Vo > 0 \tag{7.44}$$

and

$$156 \quad Vo^2 > 0 \tag{7.45}$$

i.e.

$$0 < Vo < 0.5 \tag{7.46}$$

This limitation on the vehicle speed supports some of the earlier findings. With the sensor in front of the back axle, the vehicle is unstable when driving backwards, i.e. Vo must be positive. Also as the vehicle speed increases the system goes unstable. This is borne out by observation where at speeds higher than 0.5 ms^{-1} the vehicle shows oscillations in its lateral position when cornering. This is also shown in Table 7.8 which shows the theoretical response when the vehicle speed is 0.8 ms^{-1}. At speeds below 0.5 ms^{-1}, the vehicle is observed to follow the curve smoothly with an offset or steady state error of about 100 mm.

To allow for greater vehicle speeds, one of the system parameters must be altered. Since it is usually inconvenient to change the position of the sensor or the vehicle wheelbase (!) or the steering motor, then either the gain of the closed loop angle demand system Ka, or the sensor gain Ks, must be altered. Ka is set to give the best possible performance from the angle demand system and so it is Ks which must be altered. The more general conditions for positive values in the first column of the Routh-Hurwitz array are given by equations B.14 and B.15 in Appendix B, i.e.

```
Ok
RUN


Vehicle response on meeting a semicircular
curve in the wire of radius  2.3 metres
At a speed of .8 metres per sec.
For the point u= 1.4

    Dw        Dv        y      Time       Att.

  26.57       38      -.109     1         -2.271

  26.57       24      -.11      2         -1.993

  26.57       13      -.08      3         -.723

  26.57       16      -.027     4          1.6

  26.57       37      -.04      5          1.555

  26.57       41      -.103     6         -.905

  26.57       27      -.134     7         -2.415

  26.57       9       -.079     8         -.371

  0          -7        .131     9          7.622

  0           37       .068     10         4.63

  0           29      -.108     11        -3.434

  0          -21      -.114     12        -4.815

  0          -41       .052     13         1.525

  0          -5        .146     14         5.989

  0           41       .032     15         1.97

  0           25      -.126     16        -4.786

  0          -26      -.105     17        -4.739

  0          -39       .07      18         2.228

  0           2        .143     19         5.949

  0           42       .01      20         1.09
```

Table 7.8 - Vehicle Response on meeting a curved wire
-4 VO=0.8 m/s

```
Ok
```

$$Ks \; Vo < 3.33 \qquad \text{(B.14 repeated)}$$

and

$$Vo \; (1 + 3.4 \; Ks) < 10.93 \qquad \text{(B.15 repeated)}$$

For speeds up to 1 ms^{-1}, these give

$$Ks < 3.33 \qquad (7.47)$$

and

$$Ks < 2.92 \qquad (7.48)$$

Thus for speeds up to 1 ms^{-1}, the sensor gain must be reduced such that it is less than 3 $V \; m^{-1}$. Although this leads to stability at higher speeds (i.e. between 0.5 ms^{-1} and 1 ms^{-1}), the reduced sensor gain means that the vehicle fails to follow tight curves in the wire at reduced velocities. This is because the reduced sensor gain decreases the phase margin at the 0dB crossover point and only the increased velocity can make up for this. Thus the sensor gain and vehicle speed are very closely linked, and this explains why in commercial systems the vehicle speed is not continuously variable. Normally the speed can be preselected at usually one of three possible values and then the vehicle runs at that speed constantly. Some vehicles do reduce the speed on cornering but again this is only to one preselected speed. The problem is further alleviated by using only gentle curves in the system layout.

Thus the vehicle steering is represented by a conditionally stable system. The various system parameters must be adjusted such that the vehicle remains stable within all of its operating conditions. In presently available systems this means restricting the velocity of the vehicle to one of several preselected values and also limiting the curvature of track permissible on the system. In practice, these are not serious limitations on the vehicle performance.

7.7 SUMMARY

The investigation into the magnetic sensor reveals that two long thin coils wound on ferrites with multiple layers and arranged in a horizontal configuration not too close to the ground provide the best sensor. This specification gives the widest single valued sensor characteristic with the advantage that in the null position both coils have definite signals in them and this gives the sensor good noise immunity. The steering motor used should have as large a bandwidth as possible and this is provided by using the largest value of motor constant available. The position of the sensor must be in front of the back axle to make the system stable and the further forward it can be placed, the more stable the steering system will be. The effect of wire curvature can be represented by a disturbance to the steering angle and the action of the closed loop system maintains the difference between the two steering angles at a minimum. A consideration of system stability shows that wheel angle feedback must be present and that the vehicle speed and sensor gain are very closely related.

In practice this leads to only preselected vehicle speeds being available but this does not present any operational difficulty.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 Objectives

8.2 Conclusions

  8.2.1 The Research Programme

  8.2.2 The Magnetic Sensor

  8.2.3 The Steering System Components

  8.2.4 The Vehicle Steering Control System

8.3 Further Work

  8.3.1 The Steering System

  8.3.2 The Vehicle System

8.4 Summary

8.1 OBJECTIVES

The research work which this thesis summarises has been an investigation into the use of microprocessors to provide generalised, "vehicle independent" controllers for an automatic vehicle. The particular aspect of automatic vehicle operation considered in this report is the vehicle steering or lateral position control. The theory and practical details have been outlined in previous chapters as have the results obtained. This Chapter will draw together the conclusions which can be made from this work and on the basis of these conclusions present recommendations for further work.

8.2 CONCLUSIONS

8.2.1 The Research Programme

The first major area of work established the programme of research to be followed on the automated guided vehicle project. The viability of this programme can only be fully established in the long term but preliminary results are encouraging. Work on the first project in that programme has developed an intelligent, autonomous AGV based on microprocessor control of the vehicle functions. The five vehicle functions presently incorporated are steering, positioning, load handling, intra-vehicle communications and Vehicle Executive. These functions are all internal vehicle functions. However, the vehicle design is such that it will interface quite easily in larger, multi-vehicle systems. Thus the indications are that the research programme is adequate to develop an intelligent, autonomous, free-ranging AGV which will meet the requirements of future AGVS as established in Chapter 2, and overcome the difficulties of present AGVS as described in Chapter 3.

8.2.2 The Magnetic Sensor

The theoretical analaysis of Section 5.4 was implemented in a computer programme and results from the programme compare favourably with experimental results. The programme was used to simulate coil and sensor behaviour and enabled the following specifications for both coil and sensor to be derived. The sensor characteristic should be linear with as wide a sensor window as possible. A little flattening of the linear characteristic can both provide some deadband stabilisation and increase the width of the sensor window, but this should not be excessive. To provide as wide a response as possible the individual coils should be long and this immediately means that they are thin as well. They should also not be placed too close to the guide wire. Factors such as the number of turns on the coil and the frequency and current of the signal in the guide wire should be chosen to maximise the coil output voltage. For the same reason the coil should be tuned to the wire frequency. The maximum coil separation which maintains a linear sensor characteristic is when the coils are separated by a distance equal to the coil length. Thus for a practical system the coils should be spaced slightly further apart than their own length. The resulting sensor characteristic will look like that given in Figure 6.15 and this will allow the widest variation in vehicle speed for a given value of sensor gain.

8.2.3 The Steering System Components

(a) The Steering Motor

Although neither motor used was fully satisfactory the NECO motor did allow the theoretical response of the system to be investigated. This enabled a specification for the steering motor to be developed. For stability reasons the steering motor must be placed in a closed loop feedback system where the angle on the steering wheels is fed back and compared with the input signal. Within this loop, the speed of response of the system is directly proportional to the bandwidth of the motor. This in effect demands a high torque (high Bm), low inertia (small J) motor and the best examples of these are servomotors. However, because of the high friction in the system the motor and in-line gearbox needed to overcome this will be rather long. The nature of the load is one of high friction and low inertia and this merely reinforces the need for a high torque, low inertia motor.

(b) The Vehicle Response

Due to the relatively low speed of the vehicle, dynamic effects do not come into play and the lateral response of the vehicle is due to kinematic effects only. A mathematical model of the vehicle lateral response was developed and validated. The effect of wire curvature can be interpreted as a disturbance to the input steering angle and once this is allowed for the model is equally applicable to straight and curved wire geometries. The model allowed the important system parameters to be identified. Placement of the sensor has a critical effect on the stability of the vehicle. A sensor placed on or behind the fixed axle of a single steering axis vehicle will lead to an unstable system. By placing the sensor in front of the fixed axle, a stabilising zero is introduced to the transfer function of the vehicle lateral response. The further forward the sensor is placed, the more stable the system becomes. Increasing the speed of the vehicle makes the vehicle less stable in two ways: it increases the location of the stabilising zero and thus reduces the system phase margin, and it increases the gain of the system and thus introduces greater phase lag from the motor closed loop system at the 0 dB crossover point. Both these effects decrease the system stability. The two other important factors in the vehicle steering system are the wheelbase of the vehicle and the steering angle. The longer the wheelbase, the more stable (but less manoeuvrable) the vehicle is. Steering angle is of course the controlled variable.

8.2.4 The Vehicle Steering Control System

The hardware developed in support of this investigation has been described in Chapter 6. The resulting steering system will automatically guide the vehicle around the guide path at any forward speed less than 1/2 ms^{-1}. The curves in the test track at the sponsoring organisation are deliberately set to the tightest steering angle the test vehicle can manage. To permit the vehicle to travel at greater speeds three possible system alterations are possible: a steering motor with a larger bandwidth would allow the vehicle to travel faster on the same tight curves; gentler curves would allow the vehicle with the same motor to travel faster; a reduction in sensor gain would allow the vehicle to travel faster on the same curves with the same steering motor, but would lead to instability if the vehicle were to travel slower. In practical installations curves are generally gentler than those on the Cableform test track. If it was required to negotiate tighter curves then a vehicle with a different steering geometry (e.g. geometries (c) and (d) or (e)) would be better suited.

The steering system can accept control data from one of three sources: the hand controller, Vehicle Executive and the lateral position sensor, in that order of priority. The steering software has been written in a structured form and the steering hardware has been built on a modular design. Thus the system reliability is good and the system alterations needed to cope with any hardware changes are kept to a minimum. In particular the substitution of lateral position sensors from other projects in the development programme will require only software changes. Furthermore, steering system hardware changes (including the whole vehicle!) are transparent to Group Control, Vehicle Executive and the other vehicle sub-systems. The ability of Vehicle Executive to override the automatic steering system considerably simplifies the installation of the guide wire and enables the vehicles to operate in previously inaccessible areas.

Although the use of an intelligent steering system gives all the other vehicle controllers independence of the steering hardware, the form of the steering controller is dependent on the hardware used. In situations where the mechanical form of the steering system and the type of motor and control system used are known *a priori* , the steering controller can also be made vehicle independent. However, since present industrial trucks are intended to be controlled manually the automation of a vehicle will require at the very least the installation of a steering motor. This single factor is the one most likely to limit the vehicle independence of the steering controller.

8.3 FURTHER WORK

Further work can be identified in two areas. One area is the steering system and the other area is the larger vehicle system.

8.3.1 The Steering System

(1) The use of a servomotor to provide greater bandwidth would increase the system response rate. This would allow the vehicle to travel at a greater range of speeds for a given setting of the sensor gain.

(2) Factors leading to system stability have been identified in the theoretical analysis. Incorporation of these factors in a more sophisticated steering control scheme would improve the system performance. In particular it would allow the vehicle to travel backwards at higher velocities than are at present possible.

(3) The use of a state observer implementation of the steering control system would lay the ground for much future improvement. On the present wire guidance system its only benefit would be the elimination of the need for the wheel angle sensor. But more importantly it would provide experience in the real-time calculation and monitoring of vehicle movement, and allow much more sophisticated software controlled maneouvres to be performed. This is an essential step towards the full software control of not just the vehicle steering but the complete guidance function. Thus it provides the basis for the full free-ranging capability required in future projects of the research programme.

(4) Further work also needs to be done on the mathematical modelling and simulation of the system. Better modelling of the system friction, the torque losses and the position sensor approximation would lead to a more accurate model. The simulation could then be used to investigate various compensation techniques. Also more and better experimental validation of the vehicle lateral response would increase confidence in the theoretical analysis.

8.3.2 The Vehicle System

(1) The vehicle at present is a piece of research equipment. An engineering input is required to turn it into a product.

(2) The vehicle communications function needs to be expanded to allow the vehicle to operate in a centrally controlled multi-vehicle system.

(3) A closed loop speed control system would improve the vehicle positioning tolerances. Then data on the vehicle speed could be passed back to steering and enable the steering gain to be altered accordingly to the vehicle speed. This is needed for full software control of vehicle movement and eventually for the guidance of a free-ranging vehicle.

(4) The design and building of an AGVS requires expertise in many varied areas. Two particular areas which Cableform lack are the mechanical design and the software requirements for the management of a large multi-vehicle AGVS. The mechanical expertise is needed when installing hardware such as steering motors on the vehicles, particularly in retro-fit situations. The management aspects of an AGVS is needed when the vehicles are used in conjunction with other automatic materials handling equipment and computer based systems for stock control etc. Since this expertise already exists in other companies which have many years experience in these areas it would be fruitless for Cableform to try and develop it in-house. Rather links could be made with truck manufacturers, software houses and equipment suppliers. In this way a project team capable of supplying all the expertise and equipment needed for the design, construction and commissioning of an AGVS, at any level of complexity, could be established. This team could then supply a complete systems approach; a need which is stressed in a recent

working group report to the British Materials Handling Board on automated materials handling systems[17].

8.4 SUMMARY

This report establishes a research programme to produce a free-ranging automatic vehicle and shows that the programme is adequate for that purpose. The design of the system identifies eight sub-projects and this report considers the vehicle steering sub-project. The generalised design of the steering system has been implemented in its most simple form and this has lead to specifications for the steering motor and a wire guidance sensor being developed from a mathematical model. The system has been demonstrated practically thus validating the theory.

Future work should be aimed at using the theoretical model to improve the system performance and using the sub-system intelligence to extend the off-the-wire capability of the vehicle until it becomes a free-ranging vehicle.

LIST OF SYMBOLS

LIST OF SYMBOLS

$\underline{A}$	Matrix of coefficients
a	Radial distance from the wire
a_l	Lateral acceleration
$\underline{B}$	Matrix of coefficients
	Magnetic flux density
Bm	Motor constant
Bn	Normal flux density
Bv	Coefficient of viscous friction
C	Capacitance
C(s)	Closed loop transfer function
D(s)	Laplace transform of d(t)
d	Measured deviation of the vehicle
E	Emf induced in a coil
Em	Maximum value of E
F(s)	Laplace transform of f(t)
fb	Breakpoint frequency
fo, fr	Resonant frequency
G	Gearbox ratio
G(s)	Forward path transfer function
GH(s)	Open loop transfer function
H(s)	Feedback path transfer function
h	Height of the coil above the wire
Ia	Armature current
Im	Maximum value of i
i	Instantaneous current in the wire
J_L	Moment of inertia

K	Gain factor
Ka	Motor gain factor
K_l	Lateral response gain factor
K_s	Sensor gain factor
L	Inductance
La	Armature inductance
L	Vehicle wheelbase
	Length of the coil
M	Bode plot magnitude
Mpw	Resonant peak magnitude for a second order system
n	Number of turns per unit length
Q	Circuit Q-value
q(s)	System characteristic equation
R	Resistance
Ra	Armature resistance
Ro	Radius of turn for the vehicle back axle
Ru	Radius of turn for a point on the vehicle at a distance u from the back axle
r	Coil radius
	Radius of turn
s	The Laplace operator
T	Motor torque
	Time constant
	Sample time
Ta	Armature time constant
T_L	Mechanical time constant
Ts	Settling time
Tq	Torque losses
U	Vehicle velocity parallel to the vehicle centre line

u	Distance along the vehicle centre line from the back axle Matrix of input signals
V	Vehicle velocity perpendicular to the vehicle centre line
Va	Applied armature voltage
Vg	Armature back Emf
Vi, Vin	Input voltage
Vo	Output voltage Vehicle velocity
Vs	Sensor output voltage
$\underline{Vu}$	Velocity vector of the point at a distance u from the back axle
Vy	Y-component of $\underline{Vu}$
w	Armature shaft angular velocity Vehicle angular velocity Wire frequency
Wn	Natural frequency
Wr	Resonant frequency
x	State vector matrix Longitudinal displacement of the vehicle
y	Lateral displacement of the vehicle
yo	Half width of the sensor window
z	A system zero
α	Angle between the velocity vector of a point and the vehicle centre line Armature shaft angular acceleration
$\Delta(s)$	Laplace transform of $\delta(t)$
δ	Steering angle
δS	Area of an elemental coil segment

δv	Vehicle steering angle
δw	Wire "steering angle"
ζ	System damping ratio
θ	Angle between the magnetic flux and the coil axis
μo	Permeability of free space
μr	Relative permeability
Φ	Total flux cutting a finite coil
Φ_H	Flux crossing a search coil with its axis horizontal
Φm	Maximum value of Φ
Φ_V	Flux crossing a search coil with its axis vertical
ψ	Matrix of coefficients
	Vehicle attitude

APPENDIX A

Vertical Coil Analysis

This Appendix works out the total flux crossing a search coil with its axis in a vertical orientation. Figure A.1 shows a transverse view of the coil in the magnetic field of the wire.

From the geometry

$$a = \sqrt{z^2 + h^2} \qquad (A.1)$$

$$\text{i.e. } \sin\theta = \frac{z}{\sqrt{z^2 + h^2}} \qquad (A.2)$$

and the field at the point P is given from equation 5.35 as

$$\underline{B} = \frac{\mu o\ i}{2\ \pi \sqrt{z^2 + h^2}} \qquad (A.3)$$

Now the component of the flux density $\underline{B}$ normal to the coil at the point P is given by

$$Bn = \underline{B}\ .\ \sin\ \theta \qquad (A.4)$$

and substituting from equation A.3 for $\underline{B}$ and equation A.2 for sin θ gives

$$Bn = \frac{\mu o\ i\ z}{2\ \pi\ (z^2 + h^2)} \qquad (A.5)$$

Figure A.2 shows the same coil as viewed from above where the coil is displaced by a distance c from the x - y plane and hence from the wire which runs parallel to the x-axis

The equation of the coil is

$$x^2 + (z - c)^2 = r^2 \qquad (A.6)$$

where r is the radius of the coil. Thus the difference δx between the x coordinates of the points A and A' is given by

$$\delta x = 2 \sqrt{r^2 - (z - c)^2} \qquad (A.7)$$

The area δS of the elemental strip shown in Figure A.2 is

$$\underline{\delta S} = \delta x \,.\, \delta z = 2\, \delta z \sqrt{r^2 - (z - c)^2} \qquad (A.8)$$

Thus the magnetic flux $\delta\Phi_V$ crossing each segment of a search coil near a current carrying wire with its axis in a vertical orientation is given by

$$\begin{aligned} \delta\Phi_V &= \underline{B} \,.\, \underline{\delta S} = Bn \,.\, \delta S \\ &= \frac{\mu o\, i\, z \sqrt{r^2 - (z - c)^2}}{\pi\, (z^2 + h^2)} \end{aligned} \qquad (A.9)$$

The total flux crossing the coil is given by integrating equation A.9 between the limits z = c - r and z = c + r, i.e.

$$\Phi_V = \int_{c-r}^{c+r} \frac{\mu o\, i\, z \sqrt{r^2 - (z - c)^2}}{\pi\, (z^2 + h^2)} \,.\, dz \qquad (A.10)$$

The form of this function is shown in Figure 7.2. For a search coil wound with n turns on a ferrite of relative permeability μr, the maximum value of the induced emf Em, is from equation 5.55

$$Em = \int_{c-r}^{c+r} \frac{w\ \mu o\ \mu r\ n Im\ z \sqrt{r^2 - (z - c)^2}}{\pi\ (z^2 + h^2)} \cdot dz \qquad (A.11)$$

where w is the frequency of the signal in the wire and Im is the maximum value of the current. This is the form of the expression used in the programme for calculating a vertical search coil voltage.

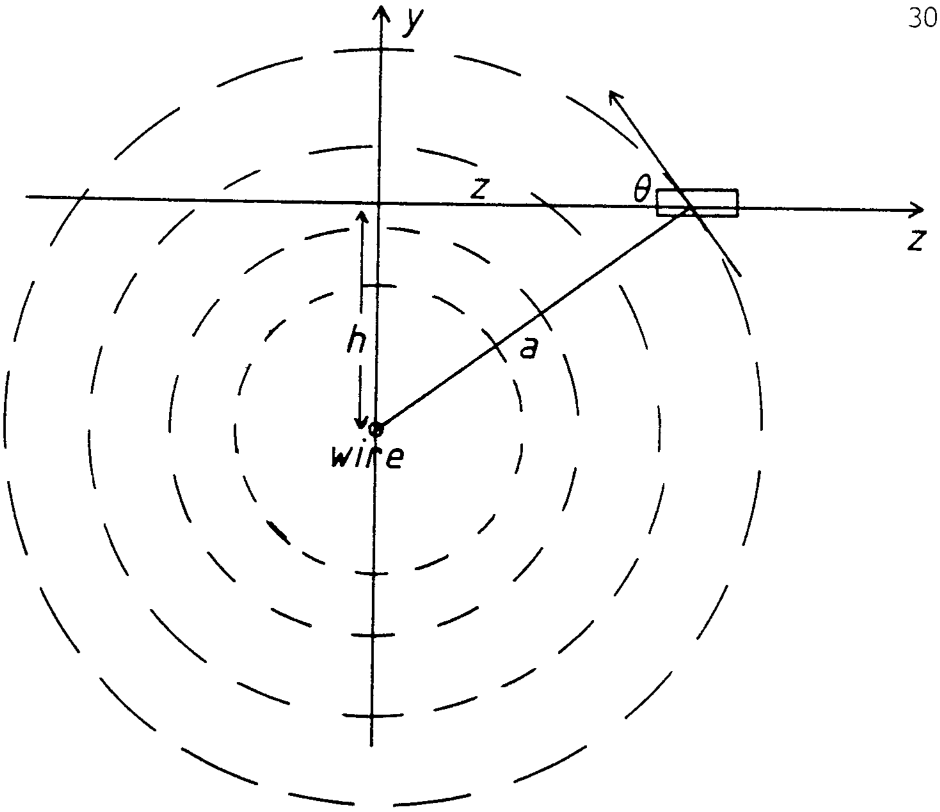


Figure A.1 - A Vertical Coil in the Wire's Magnetic Field - Transverse View

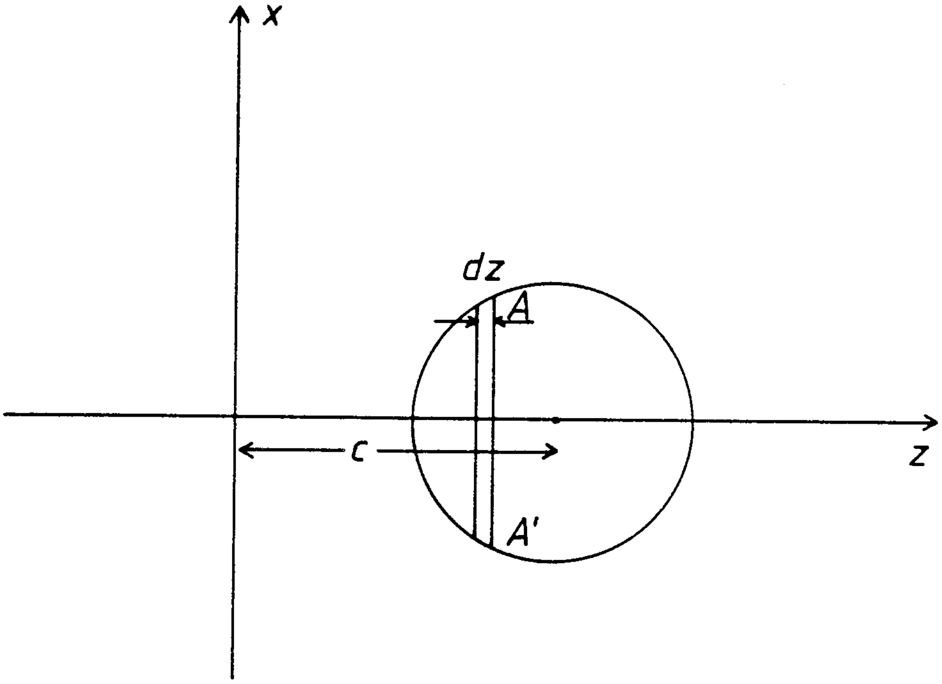


Figure A.2 - The Coil as viewed from above

APPENDIX B

The Routh - Hurwitz Criterion

This Appendix describes the Routh-Hurwitz criterion as applied to the characteristic equation of a system to determine its stability. A necessary and sufficient condition that a feedback system be stable is that all the poles of the system transfer function have negative real parts[46]. The poles of the system are given by the roots of the characteristic equation q(s). The Routh-Hurwitz criterion states that the number of roots of q(s) with positive real parts is equal to the number of changes of sign in the first column of the Routh-Hurwitz array. This criterion requires that there be no changes in sign in the first column for a stable system, and this requirement is both necessary and sufficient. The establishment of the array is given in Dorf[46] as follows

"The Routh-Hurwitz criterion is based on ordering the coefficients of the characteristic equation

$$a_n s^n + a_{n-1} s^{n-1} + a_{n-2} s^{n-2} + \ldots + a_1 . s + ao \qquad \text{(B.1)}$$

into an array or schedule as follows

$$\begin{array}{llll} s^n & a_n & a_{n-2} & a_{n-4} \\ s^{n-1} & a_{n-1} & a_{n-3} & a_{n-5} \end{array}$$

Then, further rows of the schedule are completed as follows

$$\begin{array}{llll} s^n & a_n & a_{n-2} & a_{n-4} \\ s^{n-1} & a_{n-1} & a_{n-3} & a_{n-5} \\ s^{n-2} & b_{n-1} & b_{n-3} & b_{n-5} \\ s^{n-3} & c_{n-1} & c_{n-3} & c_{n-5} \\ \vdots & \vdots & \vdots & \vdots \end{array}$$

where $$b_{n-1} = \frac{-1}{a_{n-1}} \begin{vmatrix} a_n & a_{n-2} \\ a_{n-1} & a_{n-3} \end{vmatrix} \tag{B.2}$$

$$b_{n-3} = \frac{-1}{a_{n-1}} \begin{vmatrix} a_n & a_{n-4} \\ a_{n-1} & a_{n-5} \end{vmatrix} \tag{B.3}$$

and $$c_{n-1} = \frac{-1}{b_{n-1}} \begin{vmatrix} a_{n-1} & a_{n-3} \\ b_{n-1} & b_{n-3} \end{vmatrix} \tag{B.4}$$

etc."

The steering system characteristic equation is given in equation 7.42 as

$$q(s) = s^4 + s^3\, a + s^2\, Ka\, K_1\, Ks + Ka\, K_1\, Ks\, z \tag{B.5}$$

and thus the Routh-Hurwitz array is

$$\begin{array}{c|ccc} s^4 & 1 & Ka & Ka\, K_1\, Ks\, z \\ s^3 & a & Ka\, K_1\, Ks & 0 \\ s^2 & b_3 & b_1 & 0 \\ s^1 & c_3 & 0 & 0 \\ s^0 & d_3 & 0 & 0 \end{array}$$

where $$b_3 = \frac{-1}{a} \begin{vmatrix} 1 & Ka \\ a & Ka\, K_1\, Ks \end{vmatrix}$$

$$= \frac{a\, Ka - Ka\, K_1\, Ks}{a} \tag{B.6}$$

$$b_1 = \frac{-1}{a}\begin{vmatrix} 1 & Ka\ K_1\ Ks\ z \\ a & 0 \end{vmatrix}$$

$$= Ka\ K_1\ Ks\ z \qquad (B.7)$$

$$c_3 = \frac{-1}{b_3}\begin{vmatrix} a & Ka\ K_1\ Ks \\ b_3 & Ka\ K_1\ Ks\ z \end{vmatrix}$$

$$= \frac{b_3\ Ka\ K_1\ Ks - a\ Ka\ K_1\ Ks\ z}{b_3}$$

$$= \frac{a\ [\ Ka^2\ K_1\ Ks - \dfrac{(Ka\ K_1\ Ks)^2}{a} - a\ Ka\ K_1\ Ks\ z\ ]}{a\ Ka - Ka\ K_1\ Ks} \qquad (B.8)$$

and $$d_3 = \frac{-1}{c_3}\begin{vmatrix} b_3 & b_1 \\ c_3 & 0 \end{vmatrix}$$

$$= \frac{c_3\ b_1 - 0}{c_3} = b_1 = Ka\ K_1\ Ks\ z \qquad (B.9)$$

To fill in the values of the coefficients the value of the various system parameters must be known. From equation 7.29

$$K_1 = \frac{Vo\ u}{l} \quad \text{and} \quad z = \frac{Vo}{u} \qquad \text{(7.29 repeated)}$$

For a given vehicle, the wheelbase l, and the sensor position u are set. As noted in Section 7.6 the gain of the closed loop angle demand system Ka is set to give the best possible performance from that system.

To give the most general condition the values of the sensor gain Ks and the vehicle veloctiy Vo will be left variable. Putting in the known values

$$Ka = 30$$

$$a = 3.92$$

$$u = 1.4$$

$$l = 1.15$$

hence $K_1 = 1.22\ Vo$

and $z = 0.7\ Vo$ (B.10)

Thus

$$b_3 = \frac{3{\cdot}92\ .\ 30 - 30\ .\ 1{\cdot}22\ Vo\ .\ Ks}{3{\cdot}92} = 30\ (1 - 0{\cdot}3\ Vo\ Ks) \qquad (B.11)$$

$$c_3 = \frac{3{\cdot}92\left[900.1{\cdot}22\ Vo\ Ks - \frac{(30.1{\cdot}22\ Vo\ Ks)^2}{3{\cdot}92} - 3{\cdot}92.30.1{\cdot}22\ Vo\ Ks\ 0{\cdot}7\ Vo\right]}{3{\cdot}92\ .\ 30 - 30\ .\ 1{\cdot}22\ Vo\ Ks}$$

$$= \frac{1098\ Vo\ Ks - 342\ Vo^2\ Ks^2 - 100\ Vo^2\ Ks}{30\ (1 - 0{\cdot}3\ Vo\ Ks)} \qquad (B.12)$$

$$d_3 = 30\ .\ 1{\cdot}22\ Vo\ Ks\ 0{\cdot}7\ Vo = 26\ Vo^2\ Ks \qquad (B.13)$$

Since the first two values in the array are positive, the requirement for no change of sign in the first column means that all the coefficients must be positive, i.e. for stability

$$1 - 0.3\ Vo\ Ks > 0$$

i.e.

$$Ks\ Vo < 3.33 \qquad (B.14)$$

and

$$1098 - 342\ Vo\ Ks - 100\ Vo > 0$$

i.e.

$$Vo\ (1 + 3.4\ Ks) < 10.93 \qquad (B.15)$$

For the system as developed, the lateral position sensor gain is given by equation 7.2, i.e.

$$Ks = 6\ Vm^{-1} \qquad \text{(7.2 repeated)}$$

Thus the coefficients become

$$b_3 = 30\ (1 - 2\ Vo) \qquad \text{(B.16)}$$

$$c_3 = \frac{Vo\ (6588 - 12912\ Vo)}{30\ (1 - 2\ Vo)}$$

$$= \frac{6588\ Vo\ (1 - 2\ Vo)}{30\ (1 - 2\ Vo)} = 220\ Vo \qquad \text{(B.17)}$$

$$d_3 = b_1 = 156\ Vo^2 \qquad \text{(B.18)}$$

$$\text{and} \quad Ka\ K_1\ Ks = 220\ Vo \qquad \text{(B.19)}$$

Thus the Routh-Hurwitz array becomes

$$\begin{array}{c|ccc}
s^4 & 1 & 30 & 156\ Vo^2 \\
s^3 & 3.92 & 220\ Vo & 0 \\
s^2 & 30(1-2Vo) & 156\ Vo^2 & 0 \\
s^1 & 220\ Vo & 0 & 0 \\
s^0 & 156\ Vo^2 & 0 & 0
\end{array}$$

and it is in this form that the array is presented in section 7.6.

APPENDIX C

The Intra-Vehicle Communications Network Protocol

C.1 DEFINITIONS

Each vehicle sub-system communicates with Vehicle Executive via a two port bus structure using a PIO located at ports 0 to 3. Port 2 is used as an 8-bit data communications channel. Port 0 is used as a communications control port. It has two functions. The primary function is to identify which sub-system is to be communicated with and the secondary function is to provide the handshaking lines needed by the asynchronous communications.

C.1.1 Port 0 Definition

Bit Number	Primary Function	Secondary Function
0	Reply to VE	
1	Request from CPU 1	Data Valid (DV)
2	Request from CPU 2	Data Received (DR)
3	Request from CPU 3	Data Finished (DF)
4	Request from CPU 4	
5	Request from CPU 5	
6	Request from CPU 6	
7	Request from VE	

C.1.2 Quiescent Conditions

If no communications are in progress then the state of the ports on Vehicle Executive should be:

Port 0 Bit 0 set as input

Bits 1 - 7 set as output and equal to zero

Port 2 All bits set as input

Interrupts should be enabled and the processor set to interrupt when bit 0 on port 0 goes low, (i.e. bit 0, port 0 = 0).

The state of the ports on the sub-systems should be:

Port 0 All bits set as input

Port 2 All bits set as input

Interrupts should be enabled and the processors set to interrupt when bit 7, port 0 = 1 and bit N port 0 = 1, where N is the sub-system number. The sub-system numbers are given below:

N	Sub-System
1	Steering
2	Longitudinal Position
3	Traction
4	Communications and Load Control

C.1.3 The Communications Control Word

Interrupts from Vehicle Executive (VE) to the sub-systems are achieved by Vehicle Executive placing the relevant control word on port 0. The format of this communications control word (CCW) is as follows:

Bit 0 = 0 for sub-system to receive and VE to transmit

1 for sub-system to transmit and VE to receive

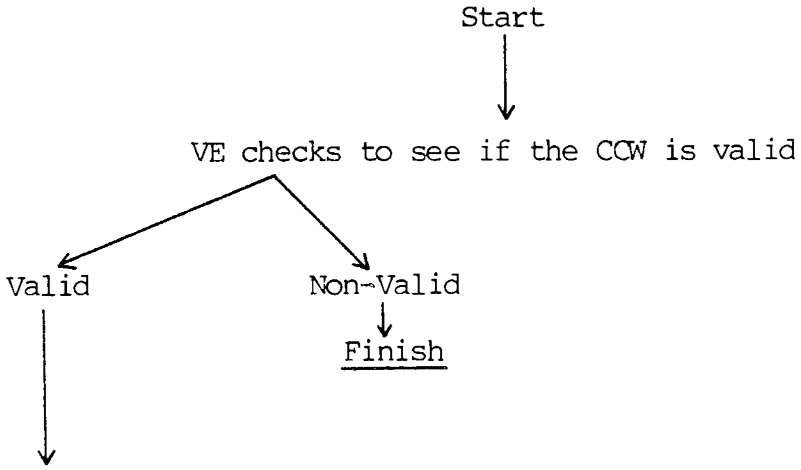
Bits 1 -6 The relevant bit is set to identify the sub-system (i.e. bit 1 for steering). All the other bits are set to zero.

Interrupts from the sub-systems to Vehicle Executive are achieved simply by the sub-system pulling bit 0, port 0 low.

C.2 THE COMMUNICATIONS PROCEDURE

Communications routines in which data are transferred between Vehicle Executive and a sub-system are always initiated by Vehicle Executive. If a sub-system wishes to communicate, then it tells Vehicle Executive of its wish to communicate and must then wait until Vehicle Execuitive initiates the communications. This it does by interrupting Vehicle Executive. When the interrupt has been recognised, the sub-system returns to its quiescent communications condition to await an interrupt from Vehicle Executive.

C.2.1 Communications Initiated by Vehicle Executive



VE disables its interrups, sets port 2 for output and sends the CCW out on port 2. It also sends out bits 1 - 7 of the CCW on port 0.

↓

Sub-system is interrupted, reads in the CCW from port 2 and sets bit 0, port 0 as an output (low)

↓

VE waits for bit 0, port 0 to go low, then it clears port 0 and sets bits 1, 2 and 3 of port 0 and the whole of port 2 for transmission (TX) or receiving (RX) according to bit 0 of the CCW. The bit pattern for bits 1, 2 and 3, port 0 is given below

Bit number	RX	TX
1	input	output
2	output	input
3	input	output

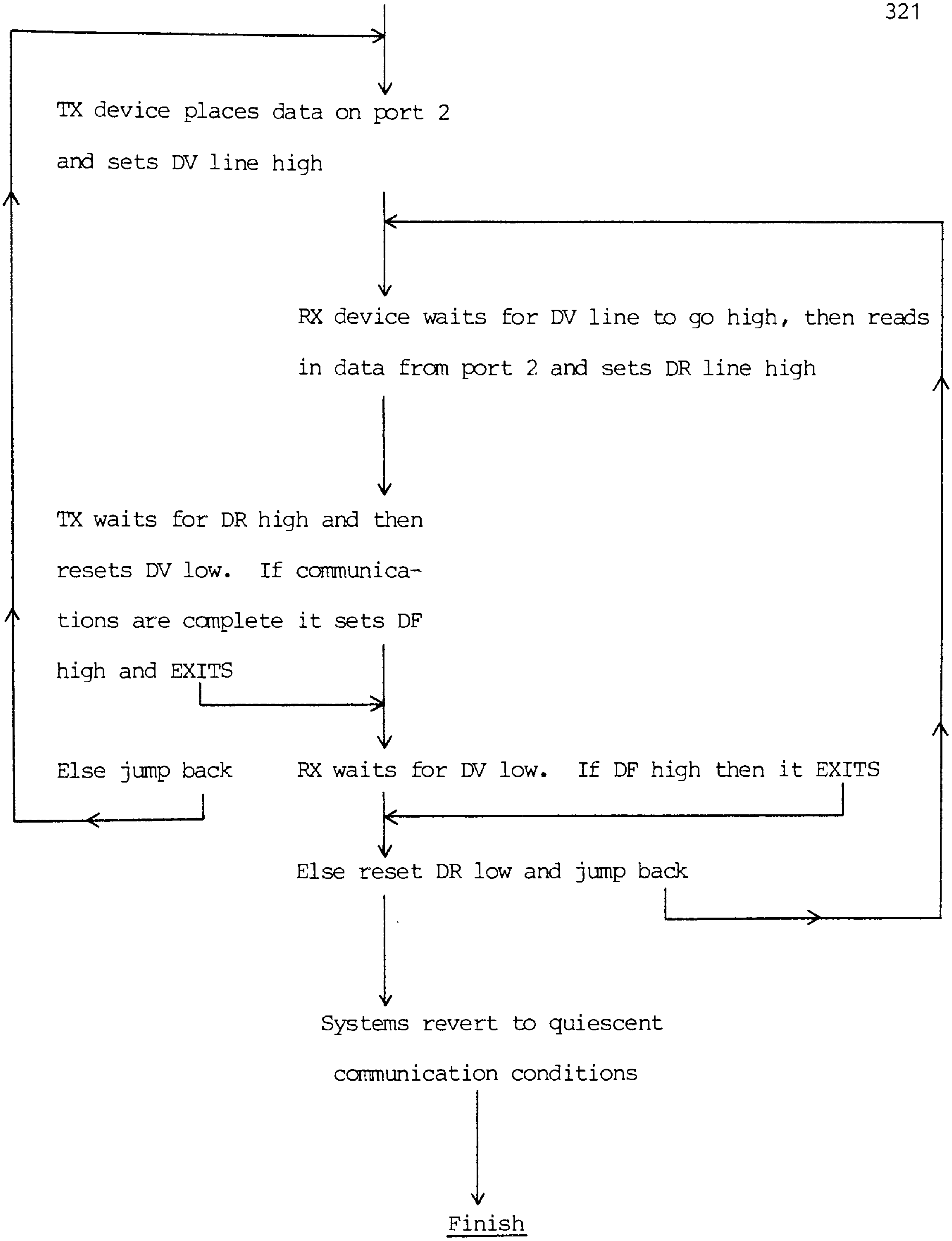
↓

Sub-system waits for bit 7, port 0 to go low, then sets bits 1, 2 and 3, port 0 and the whole of port 2 for TX or RX depending on bit 0 of the CCW. The port 0 bit pattern is the same as given above for VE.

↓

Both VE and the sub-system are now prepared for data transfer. The transmitting device waits for 5 µs, then:

↓


TX device places data on port 2 and sets DV line high
RX device waits for DV line to go high, then reads in data from port 2 and sets DR line high
TX waits for DR high and then resets DV low. If communications are complete it sets DF high and EXITS
Else jump back
RX waits for DV low. If DF high then it EXITS
Else reset DR low and jump back
Systems revert to quiescent communication conditions
Finish

C.2.2 Communications Initiated by a Sub-System

Start

↓

Sub-system checks for bit 7, port 0 = 0 and bit 0, port 0 = 1, i.e. system unoccupied. Then it sets bit 0, port 0 as output (low)

↓

VE is interrupted and sets bits 0 - 6, port 0 as input

↓

Sub-system waits for bits 1 - 6, port 0 high then sets bit N as output (where N is the sub-system number). It checks port 0 to see that no higher priority sub-system is requesting communications. If higher priority system is requesting communications THEN sub-system EXITS and tries again. ELSE it places its CCW on port 2 and sets bits 1 - 6, port 0 as input.

↓

VE waits for bits 1 - 6, port 0 high then reads the CCW from port 2 and sets bits 1 - 6, port 0 as output.

↓

Sub-system waits for bits 1- 6, port 0 low then reverts to initial conditions.

↓

VE waits for bit 0, port 0 high then jumps to VE initiated procedure.

C.3 THE INFORMATION FLOW

C.3.1 Steering (CPU 1)

Information to VE consists of two bytes

Byte 1 - bit 0 = wire captured / $\overline{\text{wire lost}}$
bit 1 = spare
bit 2 = data valid / $\overline{\text{data not valid}}$
bits 3,4 = spare
bit 5 = motor direction left/$\overline{\text{right}}$
bits 6,7 = spare

Byte 2 - bit 0 = manual / $\overline{\text{auto}}$ operation
bits 1-6 = speed from manual box
bit 7 = reverse/$\overline{\text{forward}}$ in manual

Information from VE consists of one byte

Byte 1 - bits 0-6 = angle in twos complement (+ve=left)
bit 7 = set software angle / $\overline{\text{follow wire}}$

C.3.2 Position (CPU 2)

Information to VE consists of two bytes

Byte 1 - bit 0 = at requested location/$\overline{\text{not at requested location}}$

bit 1 = slow / $\overline{\text{fast}}$

bit 2 = lost / $\overline{\text{ok}}$

bit 3 = stopped/$\overline{\text{in motion}}$

bits 4-7 = spare

Byte 2 - bits 0-7 = last location marker

Information from VE consists of two bytes

Byte 1 - bits 0-7 = desired location

Byte 2 - bit 0 = seond edge/$\overline{\text{first edge}}$

bits 1-7 = spare

C.3.3 Traction (CPU 3)

There is no information flow to VE

Information from VE consists of two bytes

Byte 1 - bit 0 = manual/ $\overline{\text{auto}}$ operation

bits 1-6 = speed in manual operation

bit 7 = reverse / $\overline{\text{forward}}$ in manual

Byte 2 - bits 0-7 = speed in automatic operation (twos complement)

C.3.4 Communications and Load Handling (CPU 4)

Information to VE consists of four bytes

Byte 1 - bits 0-6 = spare
bit 7 = obstacle detected / $\overline{\text{no obstacle}}$

Byte 2 - bits 0-7 = desired destination

Byte 3 - Manoeuvre at destination
bit 7 = software controlled manoeuvre / $\overline{\text{load handling}}$

if bit 7 = 1
bits 0-6 = angle on wheels in twos complement (+ve=left)

if bit 7 = 0
bit 0 = stop and await further instructions
bit 1 = load front rollers
bit 2 = load rear rollers
bit 3 = unload front rollers
bit 4 = unload rear rollers
bit 5 = wait 5 seconds
bit 6 = wait 10 seconds
bit 7 = take out main line contactor

bit operation when set. Else do nothing

Byte 4 - bits 0-7 = speed in automation operation (twos complement)

Information from VE consists of two bytes

Byte 1 - bit 0 = lost wire fault recorded / $\overline{\text{ok}}$
bit 1 = obstacle detected / $\overline{\text{path clear}}$
bits 2-5 = spare
bit 6 = executive load task / $\overline{\text{normal}}$
bit 7 = fault alarm / $\overline{\text{normal}}$

Byte 2 - bits 0-7 = last location marker encountered

C.4 COMMENT

This communications protocol is an ammended version of the generalised protocol and has been developed specifically for a single automated vehicle where a pre-programmed sequence of tasks replaces Group Control. In this case the communications and load handling functions have been merged and programmed with the required task cycle. To allow for manual instruction of the truck through a vehicle mounted keypad or restoration of the full communications ability with Group Control the communications and load handling functions must be separated and the generalised protocol restored. However, for the present state of the vehicle and indeed for many industrial applications the pre-programmed form of vehicle operation is all that is needed and the condensed protocol is then quite adequate.

APPENDIX D

Different Motor Models

D.1 OBJECTIVES

The mathematics of the steering motor which was developed in Chapter 5 was for a separately excited armature controlled motor. However, as mentioned in Section 5.1 the form of the model developed from the mathematics will allow the use of any motor. This is because of the discrete state space form of the model which allows the matrix coefficients or even complete equations to be altered without affecting those parts of the model which have remained unchanged. In this Appendix the mathematics for a separately excited, field controlled motor and a series motor will be considered, and it will be shown how the substitution of either of these as a steering motor will entail only minor changes to the model.

D.2 THE SEPARATELY EXCITED, FIELD CONTROLLED MOTOR

Figure D.1 shows a separately excited, field controlled motor. For a constant value of armature current the torque produced by the motor is given by

$$T = Bm \, . \, If \tag{D.1}$$

where T is the torque generated by the motor

Bm is a constant

and If is the current in the field

Applying Kirchhoff's voltage law to the field circuit

$$Vf - If\ Rf - \dot{I}f\ Lf = 0 \qquad (D.2)$$

where Vf is the voltage applied to the field

Rf is the field resistance

Lf is the field inductance

and the dot indicates differentiation with respect to time

Rearranging equation D.2 gives

$$\dot{I}f = \left(\frac{-Rf}{Lf}\right) If + \left(\frac{1}{Lf}\right) Vf \qquad (D.3)$$

The torque balance equation for the output shaft is exactly the same as previously and is given by equation 5.5 as

$$T = J_L\ \alpha + Bvw + Tq \qquad (5.5\ \text{repeated})$$

where J_L is the output shaft moment of inertia

α is the output shaft angular acceleration

w is the output shaft angular velocity

Bv is the coefficient of viscous friction

and Tq are the torque losses

Equations D.1 and 5.5 can be equated. Noting that $\alpha = \dot{w}$ and rearranging, exactly as before, gives

$$\dot{w} = \left(\frac{Bm}{J_L}\right) If + \left(\frac{-Bv}{J_L}\right) w + \left(\frac{-1}{J_L}\right) Tq \qquad (D.4)$$

Equations D.3 and D.4 are the equations of state for a separately excited, field controlled motor. Choosing If and w as the state variables x_1 and x_2, the equations can be written in matrix form as

$$\dot{\underline{x}} = \underline{A}\ \underline{x} + \underline{B}\ \underline{u} \tag{D.5}$$

where $\underline{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} If \\ w \end{bmatrix}$ and is the state vector matrix (D.5.1)

$$\underline{A} = \begin{bmatrix} -Rf/Lf & 0 \\ Bm/J_L & -Bv/J_L \end{bmatrix} \tag{D.5.2}$$

$$\underline{B} = \begin{bmatrix} 1/Lf & 0 \\ 0 & -1/J_L \end{bmatrix} \tag{D.5.3}$$

and $\underline{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} Vf \\ Tq \end{bmatrix}$ and is the matrix of input signals (D.5.4)

Comparing equations 5.61 for the armature controlled motor and D.5 for the field controlled motor, it can be seen that the system vector differential equation is exactly the same, and it is simply some of the matrix elements which are different.

Thus in the computer simulation of the steering motor, the alteration of a few matrix values will allow the same model to be used for a field controlled motor.

D.3 THE SERIES MOTOR

Figure D.2 shows the circuit diagram of a series motor. The rotating machine equations for a series motor are

$$T = K_1 I^2 \tag{D.10}$$

and

$$Vg = K_2 w \tag{D.11}$$

where T is the torque generated by the motor

I is the current in the motor

Vg is the motor back emf

w is the speed of the motor shaft

and K_1 and K_2 are constants

Applying Kirchhoff's voltage law to the circuit gives

$$V - \dot{I} L - I R - Vg = 0 \tag{D.12}$$

where V is the applied voltage

L is the motor inductance

and R is the motor resistance

Substituting for Vg from equation D.11 and rearranging gives

$$\dot{I} = (\frac{-R}{L}) I + (\frac{-K_2}{L}) w + (\frac{1}{L}) V \tag{D.13}$$

The torque balance equation on the output shaft is given by equation 5.5

$$T = J_L \alpha + Bv\,w + Tq \qquad \text{(5.5 repeated)}$$

Equating 5.5 and D.10 gives

$$K_1 I^2 = J_L w + Bv\,w + Tq \qquad \text{(D.14)}$$

i.e.

$$\dot{w} = \left(\frac{K_1}{J_L}\right) I^2 + \left(\frac{-Bv}{J_L}\right) w + \left(\frac{-1}{J_L}\right) Tq \qquad \text{(D.15)}$$

Equations D.13 and D.15 are the state space equations for a series motor. Replacing the continuous differentials by using equation 5.62 gives

$$x_1 (k+1) = \psi_1 x_1 (k) + \psi_2 x_2 (k) + T B_1 u_1 (k) \qquad \text{(D.16)}$$

where $\psi_1 = 1 - \frac{TR}{L}$ (D.16.1)

$\psi_2 = \frac{-T K_2}{L}$ (D.16.2)

$B_1 = \frac{1}{L}$ (D.16.3)

$x_1 = I$ (D.16.4)

and $x_2 = w$ (D.16.5)

and

$$x_2 (k+1) = \psi_3 x_1^2 (k) + \psi_4 x_2 (k) + T B_2 u_2 (k) \qquad \text{(D.17)}$$

where $\psi_3 = \frac{T K_1}{J_L}$ (D.17.1)

$$\psi_4 = 1 - \frac{T\,Bv}{J_L} \qquad \text{(D.17.2)}$$

and $$B_2 = \frac{-1}{J_L} \qquad \text{(D.17.3)}$$

Comparing equations 5.66 and 5.67 for the separately excited, armature controlled motor, and D.16 and D.17 for the series motor, two differences can be noted. The equations for x_1 are the same except for the differences in some of the matrix elements. The equations for x_2 differ on account of the non-linear response of the series motor. However, in the discrete implementation of the model, this difference can be easily allowed for simply by changing the one line of relevant software.

Thus in the computer simulation of the steering motor, the alteration of a few matrix values and a single line of software will allow the same model to be used for a series motor.

D.4 SUMMARY

The use of a state space model allows the use of any form of steering motor with a linear response simply by changing a few matrix values. If a motor with a non-linear response is used then the discrete implementation of the state space model will allow the use of such a motor simply by changing the relevant line of software.

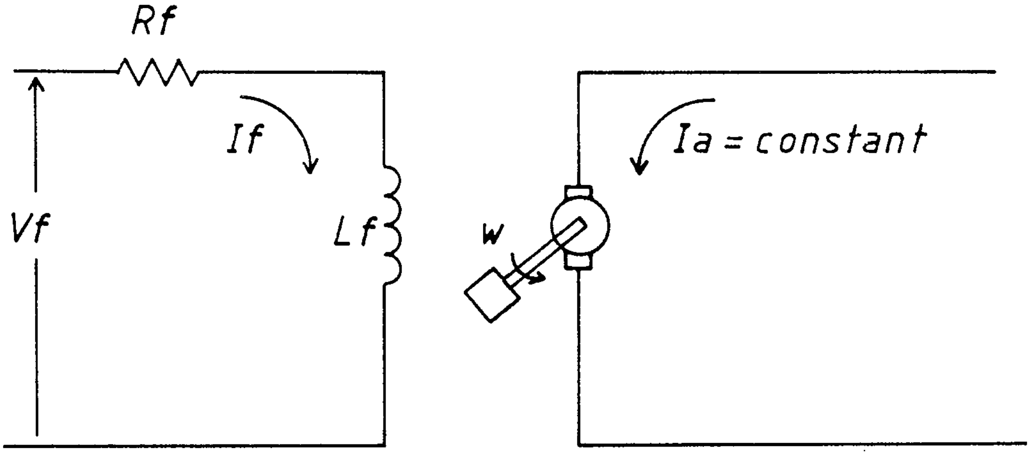


Figure D.1 - The Separately Excited Field Controlled Motor

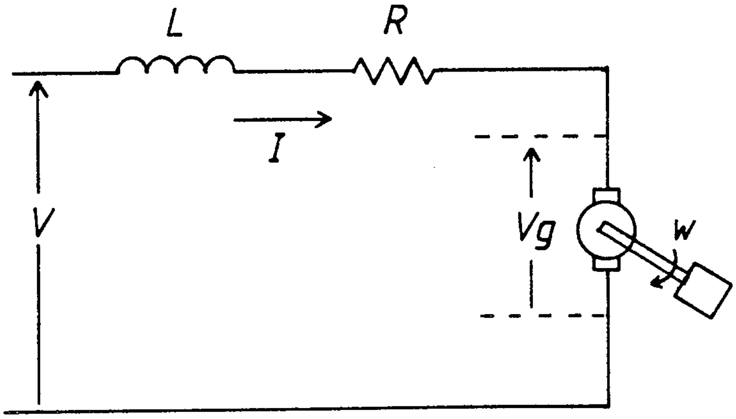


Figure D.2 - The Series Motor

APPENDIX E

The Operation of AGVS Within Integrated Materials Handling Systems

E.1 OBJECTIVES

The three examples of the use of AGVS within a materials handling system which were given in Section 2.5 dealt only with those factors relevant to AGVS operation. Here a further description of the industrial processes involved will be given in order to present a more complete picture of how AGVS can provide both cost and management benefits.

E.2 OBERNKIRCHEN GLASSWORKS

The Heye glassworks at Obernkirchen is one of the leading manufacturers of hollow glassware. One and a half million bottles are produced each day from 500 tons of vitreous glass, and this amounts to 700 palletised loads to be transported to store via an automatic covering machine and a shrinkage oven. Production is carried out round the clock on three shifts, seven days a week, without interruption. When looking at the transport system between production and storage, management wanted not only personnel reductions but also a system which could interface with the covering machine and shrinkage oven and had the flexibility to respond to organisational changes. For these reasons an automatic system was chosen. Because of the large load to be carried, tow-tractors each with three trailers were chosen, and fifteen machines were supplied by Wagner Indumat.

All non-operational vehicles wait in the parking station. When a worker at a packing machine needs a truck, he sends a demand through a local station to the central control, which assigns the first free truck to him. The vehicle travels automatically to the packing machine and stops with the first trailer in the loading position. Accurate positioning is achieved by use of a light barrier. The trailer is now manually loaded, and when complete the machine operator presses the start key and the train moves forward one trailer length.

The second trailer is then loaded, then the third. Since the loading is a lengthy operation, the vehicle makes use of this time to recharge its batteries. Thus all vehicles are constantly available. When the start key is pressed after the third trailer has been loaded the vehicle moves off towards the covering machine en route for the final store. At the covering machine, each trailer is positioned while the load is automatically covered. The train then goes to the shrinkage oven where, one by one, each load covering is shrunk. Finally the truck proceeds to the storage area where it stops automatically . The palletised glassware is now unloaded by a manned fork lift truck, and when unloaded the fork lift truck driver programmes the next destination - another packing station or the parking bay.

The operation is a fixed sequence of events and a minimum amount of automation is needed to run the AGVS. The central control merely allocates trucks when requested and monitors which trucks are operational and which are free. The system timing is controlled by manual inputs and the interface between the AGVS and the production and warehousing functions is under manual control. It is a simple yet very effective example of the use of an AGVS to cut operating costs. The use of the AGVS, whilst ensuring a 24 hour, seven day operation, has enabled 16 people to be redeployed, and it has also speeded up the material flow.

E.3 OSLO VAREDISTRIBUNAL

The integrated warehousing, distribution and administration facility in Oslo, has been hailed as 'a new concept in total distribution'[30], and 'one of the most technically advanced (warehouses) in Europe, and certainly one of the biggest'[29]. The Oslo Varedistribunal, or OVD as it is known, is an underground public warehouse which is designed to relieve manufacturers of all the specialised management and supervisory chores, and of the capital burden of distributing their goods to the various points of sale. Built largely underground on the site of an old worked-out quarry in the suburb of Ulven in Oslo it features a high degree of automation. The 30,000 pallet high bay store has 24 automatic stacker cranes, and these are served by a fleet of 75 automatic vehicles. The cranes and the vehicles are supplied by BT. It is all under the control of two computers which besides controlling the equipment operation, also provide a full suite of stock control programmes including stock level control, real-time material tracking, customer and management status reports and the production of all the necessary paperwork. They also control lighting, heating, movement of personnel, monitor the 2,200 smoke, flash and flame detectors and control the network of 5,000 sprinklers.

Incoming goods are received in one of two terminals, T1 for road arrivals and T2 for rail arrivals. Road arrivals report first to T2 where their information is entered into the computer system, before continuing onto T1, which has 12 bays for unloading. The goods are manually unloaded and placed in special floor locations where the automatic fork lift trucks can pick them up. Rail goods are unloaded at T2 and taken by automatic trucks down the 250 metre tunnel to T1. The system computers are then instructed to store the goods. The operation is now completely under automatic control. The computer sends trucks which pick up the load pallets and take them initially to a control station. Here the width, depth, height and weight are checked against the system tolerances, and a check is made upon the pallet condition. Loads rejected, for whatever reason, are sent to a repacking area for remedial action. Upon acceptance, the computer allocates suitable storage space and instructs the automatic trucks to take the pallets to the appropriate stacker crane P and D station. The automatic stacker crane then places the load in the high bay warehouse. Dispatch follows this operation in reverse taking the goods to the dispatch terminal T3.

The warehouse is on three levels and goods movement between levels is achieved with paternoster lifts serviced by the automatic fork lift trucks. There is also a manually operated small item store serviced by manned picking cranes together with a packing and order assembly area. Non-standard and rejected loads are dealt with here.

Again the AGVS provides a transport service from one location to another. However, the operation of the system is now under computer control and due to the much greater level of automation the human input is limited to instructing the system that there is a load to be stored or dispatched. The system features automatic loading and unloading at both ends of the AGVS operation and the slide on/off plus lift capability is provided by the automatic fork lift trucks. Accurate positioning of the load at the stacker crane P and D station is provided by floor mounted sensors. The computer system consists of two computers. The Lager Administrativt System (LAS) computer controls warehouse stock and the Lager Styre System (LSS) computer controls the automatic system. The LSS computer consists of a dual PDP 11/34 system with four disc drives giving 20 megabytes of storage. The LAS computer is a dual PDP 11/70 system with 200 megabytes of storage on three disc drives. The computer generates picking lists in location order, to reduce picking time and movement. It also generates check lists, dispatch notes, etc, and immediately updates stock situations.

A modern office is being erected on the surface at the warehouse site. Office accommodation may be rented and parking space is available. Office services such as telex, post, banking, duplicating, typing, etc, and canteen facilities are all to be available. Conference rooms etc are also available for hire as required, the main idea being to keep customers' own investment to a minimum. One British Company - Advanced Marketing - who already use the facility, report that costs are 50% a month less than if they had their own storage facility and personnel.

E.4 FIAT STRADA - RIVALTA AND CASSINO

In the Rivalta and Cassino plants, Fiat Strada car bodies are assembled on fully automatic lines. There are two automatic operations here; one for assembly of the side panels and one for assembly of the complete body. A car body consists of four major subassemblies; the underbody, two side panels and a roof. The Rivalta and Cassino plants produce 800 bodes per plant over two shifts. The handling system consists of 50 Digitron 'Robocarrier' pallet trucks per plant and the robot welders are Polar 6000, six axis NC machines. There are 88 of these robots in the two plants.

The side panel component parts are delivered manually to an automatic buffer store. They are then loaded automatically on a pallet truck which takes them through the welding operation to be first tack welded and then finished. The finished side panels are then taken to another automatic buffer store. The sequence is the same for the welding of a complete body except that the component parts are now the four major subassemblies. The finished car body is then automatically unloaded onto a power and free conveyor to be processed in the rest of the factory.

Here again the AGVS simply provides the transport service from one location to another and it is the automatic load/unload facility, this time provided by the buffer stores, which allows for the large degree of automation. The computer control is effected by two PDP 11/70 computers with 430 digital inputs and 590 digital outputs. The main computer tasks are:

- Simultaneous control and map management of 50 AGV's.
- Control and monitoring of 44 welding robots.
- Control and monitoring of buffer store input queues.
- Evaluation of the quality of the spot welding by analysing the welding current signals of each robot.
- Printing of quality reports.
- Back-up functions in case of system failure.
- Direct and continous dialogue with operating personnel.
- Establishment of production statistics.
- Estabishment of failure statistics for system critical point analysis.
- System monitoring for preventive maintenance.
- Diagnostic aids.

It is the flexibility of the system which is the major advantage quoted by Fiat. Four different car models, which can be mixed randomly, can be accommodated on this one line without retooling. Conventional methods would demand multiple lines. Furthermore, the major system components, i.e. handling equipment, robot welders, computer and buffer stores, are non-specific and need not be changed to allow for new models. Only 30% of all components are specific to the model line and so retooling is not only swifter, but is also much cheaper than on conventional lines.

E.5 SUMMARY

Automated Guided Vehicle Systems provide the load transport function within a materials handling system. They can interface equally well with manual or automatic operations, but it is in automatic oprations that their full capabilities and flexibility are used. In providing the transport function they can replace the traditional production line, and their flexibility means that they become a non-specific item thus reducing investment costs. The controlling computers can provide all the relevant management statistics and paperwork. Thus the automation provides both cost and management benefits.

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