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Modelling intelligent control of material handling equipment in a distribution centre.

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MODELLING INTELLIGENT CONTROL OF MATERIAL HANDLING EQUIPMENT IN A DISTRIBUTION CENTRE

by

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ABSTRACT

In an increasingly automated environment, the control of material handling tasks in a goods distribution center is an activity which requires the fusion of various disciplines of engineering in order to identify the appropriate automation tools which could prove beneficial. Various factors influence the effectiveness of automated equipment in a goods distribution centre. It is necessary to control not only scheduling and routing of goods, but also material handling equipment, which are becoming increasingly autonomous. This dissertation addresses the problem of devising a control system so that (a) material flow and (b) material handling equipment are both controlled. A discrete event modelling formalism is employed, and the concept of fuzzy logic is applied for controlling an automated goods transporting device. This approach is a significant departure from currently used techniques of modelling control in a distribution center, and opens up a very broad based research area.

The growing body of knowledge about intelligent control and knowledge based systems is an area of research which is very active. Control of automated vehicles is a thoroughly explored area, and answers are waiting for the appropriate questions. This dissertation adopts an integrated approach to the problem of modelling material handling automation, taking into consideration the twin aspects of equipment control and control of goods flow. The discrete event modelling formalism has been employed and autonomous positioning control has been modelled and simulated considering adaptive and fuzzy control strategies.

The constraints to automated guided vehicle velocity are discussed and a simulation study in SIMAN, a simulation and analysis software, is performed to examine the variation of queue length for a range of AGV velocities and pallet interarrival times. The objective behind the simulation is to come up with AGV velocities and pallet interarrival rates for which the system would perform satisfactorily. This is an essential part of designing for autonomous control.

To my wife and our parents

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NOMENCLATURE

a	Acceleration
a_t	Torque limited acceleration
a_{curved}	Acceleration around curved paths
a_{max}	maximum acceleration of AGV
a_{normal}	Normal component of acceleration
a_{fric}	Friction limited acceleration
$a_{tangential}$	Tangential component of acceleration
A	Area of image
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AS/RS	Automated Storage and Retrieval
AVI	Average velocity index (m/s)
c.g.	Centre of gravity
dA	Incremental area equal to one pixel
DC	Distribution Center
DCCS	Distribution Center Control System
e	$t-t_L$
f	Acceleration of AGV
g	Acceleration due to gravity (9.81 m/s^2)
h	Height of centre of gravity of AGV
m	Mass of AGV with load
m_{AGV}	Mass of AGV
[P]	The process "Carry pallet loads from staging to conveyor"
R, R_{curve}	Radius of curved path
r_w	Radius of drive wheel of AGV

s	Current state, distance
Δs	Increment in distance "s"
S_M	Discrete event simulator for event M
t	Time
Δt	Increment in time 't'
ta(s)	Min { All the t_l values of overlapping events }
t_L	Time of lase event
t_N	Time of next event
v_1, v_2	Initial and final velocities
Δv	Change in velocity 'v' or $v_2 - v_1$
WB	Wheelbase of AGV
W_i	Time window
x	Input variable, Distance along 'x' coordinate

Greek Symbols

α	Angular acceleration
δ_Φ	Internal state transition
δ_{ex}	External state transition
λ	Interarrival time of pallets (in batches)
Φ	State variable
μ	Coefficient of friction
σ	Current state time duration of an event in the absence of external inputs
τ	Torque
ω	Angular velocity
ς	Fraction of process completed

1.0 INTRODUCTION

Handling and distribution during the process of goods flow from the production stage to the consumer, account for 30%-70% of the cost of manufactured consumer goods (Matson, 1991). Often automated material handling can bring about a reduction in the cost of goods distribution. This economic aspect makes it important to get a better understanding, through research, of automated control of material handling.

The problem of incorporating automation in material handling tasks has been the subject of much research. Currently, automation can provide a lot of services to the material handling community. Available technology has to be understood, and the possible consequences should be evaluated beforehand. One motivating factor for the trend towards automation in the material handling industry is that many of the tasks in material handling are inherently unsuitable for humans because of the physical labour entailed. The repetitive nature of the tasks in goods distribution centres also make them extremely tedious at times.

A large proportion of consumer goods pass through one or more goods distribution centres. A distribution centre (DC) can be a very large system and elaborate modelling is required to represent the behaviour of the entire system. Automated material handling with automated guided vehicles (AGV) and automated storage and retrieval systems (AS/RS) is often chosen as an appropriate goods handling method in a distribution centre. Modelling automated handling in the entire distribution centre is a big task, and in order to restrict the size of the problem, the research presented is focussed on modelling and simulating automated control of material handling equipment in the process "Carry goods from staging area to conveyor." The process is a part of the "Receiving and unloading" functionality in a distribution centre.

In the context of modelling the control system, a distribution centre may be described as a modern warehouse. The change in terminology is indicative of the fact that whereas goods storage is the primary function of a warehouse, goods distribution is the most important function in a distribution centre. Of course goods distribution is a mandatory function of a warehouse as well; and an important means of reducing warehousing costs is to improve distribution and reduce storage. Modelling automated goods handling is a fairly well researched area. However, the materials handling research community has stated that a major problem with research on modelling and simulation of the control system of material handling equipment is the lack of an integrated approach to the following two aspects of control (White, 1989).

(i) Determining the goods flow volume, path and sequence of goods movement which will optimize objective functions related to cost and time.

(ii) Controlling the actuators responsible for the movement of material handling equipment.

This deficiency is addressed in the research, and defines the research objectives:

1.1 Research objectives

- To model intelligent material handling in a distribution centre considering the effect of dynamic constraints on the velocity profiles of an automated handling equipment (a sideload forklift AGV).
- Modelling and simulating controlled vision-based positioning of an AGV.
- Simulating the process model and drawing conclusions about the possible benefits of autonomous material handling.

1.2 Motivation for research

The genesis of this particular research lies in an article which appeared in IIE Transactions in 1992, where a Program Director at the National Science Foundation (NSF) in USA, Louis

Martin-Vega, identified "Intelligent Materials Handling Initiative" as a very important research area of the NSF. Some facts regarding this research topic emerged during a workshop conducted by the DDM.[1] The DDM co-sponsored the 1990 Material Handling Research Colloquium in Hebron, Kentucky. This workshop discussed research being carried out in the area of "Intelligent Materials Handling." Some excerpts from the article presented below indicate the role of the mechanical engineer and the importance of an "integrated" approach to research in "Intelligent Materials Handling."

1.2.1 Excerpts from the NSF report

Venue: 1990 Material Handling Research Colloquium, Hebron, Kentucky.
Topic of discussion: "Intelligent Materials Handling Initiative."

"..major advances in this area would require the collaboration of a larger set of disciplines...The major elements missing at the workshop were members of the mechanical engineering, .. communities."

"In order to reach these communities[2], NSF program directors in mechanics and structural systems, dynamic systems and control, information, robotics and intelligent systems, and design and manufacturing were approached and involved in the design of this initiative. Their interest and willingness to pool resources resulted in the implementation of the first cross-directorate initiative between ENG and CSIE.[3] The announcement required

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[1] The engineering directorate(ENG) of the National Science Foundation (NSF) contains the Division of Design and Manufacturing (DDM).

[2] Mechanical Engineering, Electrical Engineering and Computer Science.

[3] Directorate of Computer and Information Science and Engineering in the NSF.

cross-disciplinary groups willing to explore software and information linkages as well as applications in non-traditional environments. The suggested topic areas included the development of knowledge-based software and multi-sensor systems for designing and controlling automation in bin-picking, kitting, palletizing, and storing/retrieving operations; intelligent transport systems such as autonomous, co-operative subsystems and free-path movement; and computer modelling that integrates data on designs, work cell characteristics, material loads and routes, flow and buffer requirements, and facility configuration."

1.2.2 Relevance to research objectives

This announcement by the NSF addresses the concerns of the Materials Handling research community. An integrated approach to tackling the problems associated with "Intelligent Materials Handling" is needed. One problem which we face in gaining a better understanding of the behaviour of a large system is that of creating a model of the system. In the initial stages of the research work, the functions and components of a goods distribution centre were examined in detail. A suitable modelling framework is required to take into account the two aspects of "control" in a distribution centre, namely, control of goods flow (path, volume and sequence), and control of material handling equipment.

The research work discussed in the dissertation provides answers to the questions:

- How does one take into account "handling equipment" control issues and "goods flow" in a goods distribution centre?
- Is it possible to devise a simple and robust positioning method to enable automated guided vehicles to rapidly pick up pallets?

The results of simulation studies demonstrate that total automation at the receiving docks is not a far fetched idea, given the available technology. The modelling method adopted is aimed at providing useful answers quickly, without attempting to develop highly accurate models.

This is justified since the system (a part of a distribution centre) modelled is "multi-facetted" and not amenable to highly accurate modelling. Large variations in parameters like pallet interarrival time, positioning error, pallet weight, and power loss in handling equipment can make an excessively detailed model meaningless. The discrete event modelling framework employed can be effectively utilized in developing a robust expert system, as discussed in chapter 9. A detailed search of related literature confirms that this is a unique approach towards unmanned control of goods flow, in the distribution centre.

1.3 The Distribution Centre as a Large System

A DC regulates the flow of a product at various stages of the production-consumption process. Planning is necessary to ensure that DC resources are used in an optimal manner so that goods and information flow is effectively controlled. Thus, based on the premise that the DC is a flow regulating system, it may be divided into four dimensions or sub-systems: operating strategy, functionality, control system and resources. These sub-systems can be represented as sets containing a number of elements which interact with each other.

1.3.1 DC Operating strategy

The overall plan of operation in the DC is contained in the operating strategy. The planning activity required to generate the operating strategy has traditionally been performed by management personnel. The overall objective of the operating strategy is the satisfaction of the overall DC goals subject to resource constraints. The primary goals of the DC are to provide customer satisfaction and to optimize the use of resources.

Sub-goals of the DC specify `how to' achieve customer satisfaction and `how to' achieve efficient use of resources. These goals are dynamic in nature due to variation in customer requirements and constraints, for example, type of product access required in the DC [Need to retrieve large volumes at once or in small batches] speed of storage and retrieval required, speed of information acquisition and information processing [eg. machine vision can be quite time consuming if image analysis is required]. If the DC is used as a retail outlet, customer service, safety, physical environment, material handling equipment and value addition support activities are factors to be considered. The sub-goals are tied in with information from the external environment, comprising sales forecast, raw material prices and variable factors in transportation and logistics. This information can bring about a change in the sub-goals. Determining the effect of change in the sub-goals and making appropriate decisions is a part of the operating strategy. These decisions have to be responsive to the external and internal environment of the DC.

The operating strategy in the DC consists of two types of plans: (a) Strategic master plan (b) Contingency plan. The former anticipates predictable future changes in the DC environment and sub-systems, and plans are made ahead of time. Examples of these changes are: (i) space shortage (ii) personnel shortage (iii) product line changes (iv) future inventory levels and product mix. A precise time frame for the change cannot be established since it is very difficult to predict when the changes will occur. The contingency plan is a preparation for unexpected developments, and goes into effect when the strategic master plan is not applicable. The absence of a contingency plan would lead to a situation requiring crisis management.

1.3.2 DC Functionality

The functionality dimension of the DC traces the events related to the flow of goods into, within, and out of the DC. The dimension can be divided into four sub-systems:

(i) Goods reception

This function involves one or more of the following operations:

(a) Advance notice (dispatch and receipt) of anticipated arrival of goods at the dock.

(b) Downloading of detailed shipment information to DC control system.

(c) Unloading goods at the dock.

(d) Inspection, and

(e) Transporting goods to staging area.

(ii) Storage and retrieval

This function includes:

(a) Identification and tracking of full and empty loads.

(b) Selection of storage sites.

(c) Moving goods to storage.

(d) Stock location and inventory counting.

(e) Order picking from storage.

(iii) Dispatch

Goods dispatching involves the following activities:

(a) Routing and moving picked goods to staging lines.

(b) Loading goods at dock.

(c) Updating customer order files.

(iv) Value addition activities

These include changing product attributes (customizing or reconfiguring) or performing a processing activity on the product, An example of such a value addition activity is the 'Green Giant' company warehouse in Tecumsee, Windsor, where Brand X corn was canned for 25 years without a label, as brand X did their own labelling elsewhere, after Green Giant shipped from their warehouse. In 1995, Green Giant added a 'labelling line' in the warehouse, making a profit of 1¢ per can.[4] Many such activities may be carried out on the goods while in transit through the distribution centre.

1.3.3 DC Control System (DCCS)

The DCCS has three basic objectives:

(i) Identify and coordinate the work to be done.

(ii) Direct the accomplishment of the work so as to maximize performance (customer satisfaction and resources productivity).

(iii) Signal generation and interfacing with sensors and material handling equipment for the purpose of intelligently controlling the motion of material handling equipment.

The strategy followed by the control system is determined by the operating strategy dimension. A feature of an intelligent control system is that it can formulate sub-goals for the control system which determine signal generation and signal flow paths in the control algorithm. Reformulation of sub-goals is sensitive to the state of the DCCS. This is dependent on:

- State of the functionality and resource dimensions and
- Output from the operating strategy dimension.

As in the case of the DC, the sub-goals of the control system provide answers to the question `how to' achieve the primary control system objectives, which are listed at the beginning of this section.

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[4] Private communication with Dr W.P.T.North, Professor of Mechanical and Materials Engineering, University of Windsor, Windsor, ON N9B3P4.

1.3.4 DC resources

Space, equipment and personnel comprise the resources of a typical DC. The most valuable resource responsible for the efficient management of the three basic resources is information. [The management of information in the DC is a complex problem and is not related to the objectives of this thesis. One of the major assumptions here is that appropriate information is available as and when required, without significant delay].

(i) Space: This refers to storage space in the DC. Layout is a factor which affects the utilization of space, and therefore layout optimization contributes to space optimization.

(ii) Equipment: Storage racks, pallets, material handling equipment, sorting and packaging equipment, sensors and signal processing equipment, labelling equipment, etc. which play a part in achieving DC goals are termed DC equipment.

(iii) Personnel: Management, DC technical staff, and operators of material handling equipment have very important roles to play in ensuring that the DC goals are achieved.

Optimum use of resources is achieved by meeting customer requirements and minimizing the costs associated with the resource subject to the constraints of:

- Ensuring safety and comfort of personnel.
- Complying with regulations regarding resource utilization.
- Ensuring that flexibility is not compromised.

1.4 Format of dissertation

The topics covered and their sequence is as follows:

- Survey of research.

A survey of literature in related topics is carried out to identify concepts which may be used in the current research.

- Modelling the goods handling process.

The theoretical basis for modelling goods handling is examined and a discrete event model is built up of the handling process.

- Automated guided vehicle velocity profiles.

Velocity profiles of the AGV are plotted, taking into account dynamic constraints to motion. The average velocity was determined from these profiles and integrated into the overall process model.

- Positioning using vision feedback.

A scheme for positioning the AGV is suggested. The method is experimentally validated and modelled. Controlled positioning is simulated and the positioning velocity is obtained from simulation runs.

- Simulation of process.

Goods movement is simulated with a system theory based simulation package, SIMAN[1]. The velocity of the AGV is obtained from the AGV velocity and positioning models.

- Results.

The AGV velocity profiles and the results of the simulation runs are presented.

- Discussion.

This section contains a discussion of the results obtained from the simulation.

- Scope for Future Research

The research presented can be utilized in developing an intelligent handling system which will respond to simulation outputs to take pre-emptive action to keep the material handling process in control.

2.0 LITERATURE REVIEW

A search of literature related to automated material handling reveals a large number of research papers on problems related to selecting appropriate material handling equipment. Simms (1995) discusses the factors promoting increased automation, which has created significant changes in material handling over the last few decades. The move towards centralizing goods distribution systems is seen to be a major contributing factor to increased automation in material handling. An indication about the importance of research in this area is provided by the existence of the Material Handling Research Center, which started as a research project in the Georgia Institute of Technology, and has since grown rapidly (Pence, 1994). A carefully designed automated material handling system can prove to be beneficial in significantly enhancing the performance of manufacturing operations (Witt, 1995).

One important aspect of the problem of designing an appropriate automated material handling system is equipment selection. It is very important to maximize the productivity of expensive automated material handling equipment, and while decisions about equipment selection can be influenced by a large number of factors, aids to decision making can be provided by using knowledge based systems for coming up with appropriate specifications and suggestions. The utilization of the system also depends on the scheduling rules employed, and dynamic rescheduling can be a possible solution for the problem of optimizing AGV scheduling (Interrante, 1994). Research presented in this dissertation singles out a subsystem (Material handling at unloading docks/staging area) of one aspect (equipment control) of the material handling system employed at goods distribution centers. The focus of this chapter, therefore, is to discuss available literature in topics related to "modelling automated distribution centre control systems (DCCS)". A broad overview of current literature in this area is presented in section 2.1. Subsequently, the area of interest is narrowed to focus on discrete event modelling and autonomous vehicle control including vision based control.

2.1 The distribution center control system

A review of publications on warehouse control system modelling and related topics indicates that the principal research techniques may be divided into the categories of :

- Prototype building.
- Analytic modelling and network analysis.
- Simulation.

In the context of modelling automated material handling in a DC, it is instructive to examine literature related to modelling control of mobile manipulators, since control and navigation of mobile robots is very similar to control of material handling equipment.

Research on modelling operational control of large systems is also of interest as a DC is a large multifaceted system, and modelling such a system requires the integration of different model formalisms. Therefore the following additional categories were included in the survey:

- Mobile manipulators.
- Sensor application.
- Large system modelling.

2.1.1 Prototype building:

An example was found in the prototype of an automated warehousing and manufacturing plant in Oviedo University, Gijon, Spain. A description of the warehouse is provided by Sirgo (1990). The project explores control aspects of automated material handling equipment, but does not address some important aspects of intelligent control, specifically the issue of flexibility and autonomous operation, or the importance of a broad modelling framework where equipment control can be integrated with flow control.

2.1.2 Analytic modelling and network analysis:

This approach can be used to optimize resource utilization based on an objective function. A static model has been used to study warehousing systems at the Fraunhofer-Institute (Junemann, 1988). Analytic models proposed by Francis (1974), Berry (1968) and Roberts (1972) have considered particular dimensions of warehousing. Network analysis of resource utilization problems has been performed by a large number of researchers {Kiran (1989), Egbelu (1988), Gaskins (1989)}.

Analytic modelling of automated material handling has resulted in a large number of algorithms where the potential for improved layout design and improved productivity is investigated. It has also provided the basic mathematical formulation on which simulation of material handling systems are based. Typical research areas are guidepath design of AGVs and AS/RS equipment, and operating strategy of an automated material handling system. Important work in developing algorithms for conflict resolution of AGVs, especially when the complexity of traffic control is increased as with bidirectional AGVs motion (Egbelu, 1986) provides tools for static routing for material handling equipment. If it is required to recalculate the route at frequent intervals or when the automated equipment reaches a node, a relatively fast algorithm which optimizes an objective function is required. This may be interfaced with the equipment controller to take decisions regarding which route to follow. An excellent discussion of this type of algorithm is provided by Egbelu (1991) where a linear programming formulation is utilized to minimize service response time by selecting optimal dwell points in an AS/RS system.

2.1.3 Simulation of DCCS:

The simulation approach is particularly suitable to the study of large systems like the DC and its sub-systems. A review of the literature on warehouse analysis and design reveals that computer simulation using simulation packages is a technique that is widely used to make predictions regarding the optimum use of warehousing facilities. This approach has proved very useful in designing a warehouse and in modifying operations and layout so as to improve productivity. Simulation is an important tool in researching material handling systems. Egbelu (1988), Linn (1987), Chang (1986), Ozden (1988), Ashayeri (1984) and Kawabata (1985) demonstrate the many capabilities of powerful simulation packages currently available. The problem of selecting storage in the warehouse and optimizing inventory relocation strategies have been investigated by Mansuri (1991) who has evaluated the advantages of various storage options based on a simulation study. Caedarelli (1995) has optimized handling and storage system performance by using simulation in the integrated model of handling equipment and a wafer manufacturing process. An interesting aspect of simulation modelling is the 'evolution' of a model through various stages in response to user requirements. This aspect has been discussed by Hunter (1994).

Solutions to the problem of simulating large systems have been suggested, as in the paper by Ruger (1990). These deal with the construction of generic control elements possessing a high degree of reusability, and employing an object oriented approach to model control logic in a logistics system. However, the root of the problem of designing intelligent material handling systems lies in the difficulty of creating a model which is universally applicable to a large variety of system configurations and is integrated with a controller for manipulating material handling equipment. There have been attempts to solve this problem by designing simulators which facilitate AGV modelling (King, 1995).

2.1.4 Mobile manipulators

Control and navigation of mobile robots is very similar to control of material handling equipment. Based on this premise, a survey of recent literature on this vast research topic was undertaken. Extensive research related to navigation and motion control of manipulators has been carried out in recent years by Horn (1992), Feng (1990), Dean (1990), Bruce (1991) and Knieremen (1991). The major focus of these researchers was on the electro-mechanical motion control system. Stability of the control system and intelligent control have been examined by Pomerbau (1991) and Garcia-Cerezo (1991). A method of representing the state of a non-linear system with a linear equation, which holds promise for simplifying the representation of large autonomous systems similar to the warehouse control system, has been discussed by Zimmer (1992).

2.1.5 Sensor application

A key feature of an automated control system is the use of sensors, and therefore research in the field of sensor applications in mobile electro-mechanical manipulators is of interest. Komoriya (1991), Tsudo (1991), Yamaguchi (1992) and Romiti (1992) have worked in the rapidly evolving field of new and modified sensor technology which have applications in material handling and robotics. Zapata (1990), Donald (1991), Egeland (1991), Komoriya (1991) and Wollnack (1992) have suggested methods of interfacing the control system with different sensors in order to accomplish particular objectives.

2.1.6 Large system modelling

Research related to the modelling of a warehouse control system requires an understanding of system science and modelling as currently applied to the field of material handling and logistics. To this end, several recent publications on modelling material handling and logistics systems were identified. Prominent among these, in terms of the usefulness for this particular application, are the works of Zeigler (1991), whose paper on discrete event system modelling formalism offers an algorithm which can be used to conduct multiple simultaneous explorations of model behavior. Some discussion regarding the method of discrete event modelling is found in the paper by Sevinc (1990) who points out that the process of model abstraction serves the purpose of learning more about model behavior and inferring properties which may not be evident.

A formal description of the control structure for a mobile robot has been discussed by Badreddin (1991) and by Sowmya (1991) and can provide a guideline for a formal description of the control structure of material handling equipment used in the warehouse. Ruger (1990) in his paper on logistics systems discusses control logic modelling strategies, which has similarities to control logic in the warehouse. Other recent papers on system modelling which are of interest in terms of applicability in modelling warehouse control systems are those by Kalashnikov (1991), Lee (1990), Troch (1992), Soloveva (1991), Luh (1991), Kozak (1992), Lunze (1992), and Wolstenholme (1992).

A description, or formalism for a system is necessary prior to modelling it or attempting to control any aspect of the system. While discrete event formalism for high level system abstraction has received attention only recently, symbolic formalisms have been utilized for some time for knowledge representation in artificial intelligence (AI). Formalisms of knowledge representation schemes in AI provide adequate information about knowledge based systems and interactions among the sub-systems and the environment, but are usually not capable of adequately representing the dynamic nature of a control system (Zeigler, 1991). In contrast, high level abstraction of system behavior is difficult using the difference and differential equation formalism, and provides virtually no information regarding the system environment. This is because the representation of logic and interaction of sub-systems is dependent on variables which cannot always be analytically determined. The performance of the system may be conveniently studied by treating it as a discrete event system where events are triggered by threshold sensors. This method of analysis, obviously, is very different from the differential equation formalism, where the continuous change of a dependent parameter in response to a completely determinate change in an independent variable is examined.

It is observed that the following three approaches to system modelling are frequently encountered.

(i) Symbolic formalisms for knowledge representation in systems which exhibit artificial intelligence (AI),

(ii) Difference/differential equation formalism to analytically represent the behavior of control systems, and

(iii) Discrete event formalism to represent event-based control.

Formalisms of knowledge representation schemes in AI provide adequate information about knowledge based systems, interactions among the sub-systems and the environment, but are usually not capable of adequately representing the dynamic nature of a control system (Zeigler, 1991). In contrast, high level abstraction of system behavior is difficult using the difference and differential equation formalism, and provides virtually no information regarding the system environment.

The discrete event modelling formalism employed in the paper by Zeigler (1991) is well suited as a means of representing the DCCS, since it can be used as a tool for modelling material handling equipment for which analytic models are unavailable, but for which input-output relations are known. In addition, knowledge representation is also convenient.

2.2 Discrete event control

Dr. Yu Chi Ho (Gordon McKay Professor, Harvard University) in his editorial in Proceedings of the IEEE, January 1989, distinguished between human centered discrete event dynamic systems (DEDS) and continuous variable dynamic systems (CVDS). To quote: `Examples of the former are production or assembly lines, computer / communication networks, traffic systems, etc. where the evolution of the system in time depends on the complex interactions of the timing of various discrete events, such as the arrival or departure of a job...The "state" of such dynamic systems changes only at these discrete instants of time instead of continuously.'

The editorial is in agreement with the choice of a modelling framework discussed in section 2.1. Since the system is "discrete event", the controller is "event based." This line of reasoning leads us to examine literature related to "event based control" of automated systems. According to Zeigler, "in this (event based) control paradigm, the controller expects to receive confirming sensor responses to its control commands within definite time windows...determined by its discrete event system specification (DEVS) model of the system under control...the DEVS formalism is at the heart of event based control design.."

2.2.1 Discrete event dynamical systems

The discrete event system specification (DEVS) representation of a dynamical system divides the state space of the process modelled into a number of blocks equal to the cross product of the set of states of every sensor, and the set of output states generated. In his paper, Zeigler (1991) provides a detailed explanation of DEVS representation of event based process control in a discrete event dynamical system. The formalism consists of (a) basic (atomic) models and (b) interconnections between sub-systems. A basic model of a DEVS is made up of: (items 1 to 7 below are quoted from Zeigler, 1984).

1. The set of input ports through which external events are received.
2. The set of output ports through which external events are sent.
3. The set of state variables and parameters. Two state variables are generally present, ϕ, [which represents current state] and σ, [which represents time duration of the event in the current state in the absence of external inputs].
4. The internal transition function, which specifies to which next state the system will transit after the time given by σ has elapsed.
5. The external transition function, which specifies how the system changes state when an input is received-the effect is to place the system in a new phase and sigma, thus scheduling it for a next internal transition.
6. The output function, which generates an external output just before an internal transition takes place.
7. The time advance function which controls the timing of internal transitions-when the sigma state variable is present. This function just returns the value of σ.

Atomic models can be interconnected in a hierarchical structure to form a coupled model which has the following information (Zeigler, 1984).

1. The set of input ports through which external events are received.
2 .The set of output ports through which external events are sent.
3. The external input coupling, which connects the input ports of the coupled model to one or more of the input ports of the components-this directs inputs received by the coupled model to designated component models.
4. The external output coupling, which connects output ports of components to output ports of the coupled model-thus when an output is generated by a component, it may

be sent to a designated output port of the coupled model, and be transmitted externally.

5. The interval coupling, which connects output ports of components to input ports of other components-when an input is generated by a component, it may be sent to the input ports of designated components (in addition to being sent to an output port of the coupled model).

2.2.2 Modelling autonomous control

An integrated approach to modelling all the control aspects of an automated distribution centre was not found in literature. However, Schooley (1993) has developed an architecture for modelling high autonomy control systems for application in the control of space resource processing plants. The idea behind the framework can be summarized in the following excerpt: "Autonomy is the ability to function as an independent unit or element for extended periods of time, performing a variety of actions necessary to achieve predesignated objectives while responding to stimuli produced by integrally contained sensors...Requiring greater degrees of autonomy (as compared to intelligent control systems) forces the more expanded view presented by Antsaklis (1993) in their framework for autonomous control systems: Full integration of knowledge based reasoning (derived from artificial intelligence) together with perception and action components (derived from robotics and control)."

2.3 AGV motion planning

Modelling the control of material handling AGV's is one of the goals of this thesis, and to this end, a detailed consideration of literature related to movement of automated vehicles was carried out. One aspect of planning AGV motion is AGV scheduling, which involves issues such as AGV-conflict avoidance, AGV dispatching policies, and AGV routing. The work done to date on these issues considering line layout, loop layout, and more complex networks for AGV path have been summarized by Ganesharajah (1995). Evidently, efficient design is an important part of motion planning. System design takes into account the layout and scheduling aspects of AGV motion planning (Johnson, 1995). Finally, after the system design phase, the availability of a controller which will be able to operate the entire material handling system, has to be investigated. A proposed controller architecture capable of controlling an automated material handling system is discussed by Duffie (1995).

Minimization of time in the presence of dynamic constraints of vehicle motion was investigated by Schiller, (1991). The topic is very similar to one of the problems of interest, that of minimizing time required to travel a fixed path subject to dynamic constraints to vehicle speed and acceleration. In their paper "Dynamic motion planning of autonomous vehicles," the authors present a speed control method where the time of travel of an autonomous vehicle is minimized while taking into account vehicle dynamics, surface topography and surface mobility. The vehicle dynamics are modelled by the equation of motion (Newton's laws) in the form:

$$f_t t + f_q q + Rr - mgk = m\kappa n \dot{S}^2 + mt \ddot{S}$$

where t,q,n,k and r are direction unit vectors, κ is the curvature of the path, m is the lumped vehicle mass and S is the displacement vector. The vector sum of tangential, friction and reaction forces, f_t, f_q, and R are equated to the sum of the centripetal and D'Alembert's (inertia) forces on the vehicle. The equation, in an expanded form, is used to come up with feasible speed and acceleration for given limits on the friction and normal forces. The authors consider (a) Engine torque constraint, (b) Sliding constraint, (c) Contact constraint (d) Tip-over constraint (e) Velocity limit curve constraint and (f) Constraint to motion due to obstacles.

The communication technology used to guide the AGV is part of the overall design consideration during motion planning. Single wire guided AGVs often have an advantage because of simplicity, reliability and cost. The positioning accuracy is quite adequate (Kenyon, 1995).

2.4 Vision based AGV guidance

A large number of papers on this topic were encountered in literature. Vision is used in material handling not only to identify targets, but also to extract information (Cho, 1994). This aspect of vision based guidance (where the AGV responds to the information content of the target) is not addressed. Instead, we focus on efficiently identifying the location of the target. Baumgartner and Skaar (1994) have addressed this problem in their paper where they have described the theoretical development and experimental implementation of a complete navigation procedure for use in an autonomous mobile robot for structured environments. Visual cues are employed to update position. Accurate positioning is achieved by performing sensor fusion with an extended Kalman filter with visual input and wheel rotation input. The authors also propose a time independent differential kinematics of the vehicle modelled. The visual sensing of cues is of particular interest in this thesis. Elliptic ring-shaped cues are employed by the authors, and calibration curves of distance versus calibration parameters C1..C4 provide the location of the vehicle as per:

$$x_c = C_1 \frac{X\cos(\phi + C_4) + Y\sin(\phi + C_4) - C_2}{X\sin(\phi + C_4) - Y\cos(\phi + C_4) - C_3}$$

x_c is the horizontal location of a cue in the image plane of the camera, measured in pixels, and X and Y refer to the cartesian coordinates of the camera, and ϕ is the angular orientation of the camera axis with respect to the target. An interesting method of locating targets has been implemented recently using a laser scanner and a retroreflecting target (Bak, 1995). The positioning method discussed in this dissertation uses a similar imaging scheme. The complexity of the problem of extracting information from visual data has led researchers into the area of artificial intelligence and knowledge based systems (Inigo, 1995).

2.5 Fuzzy Logic Control

Although a great volume of literature exists in the area of fuzzy control of autonomous vehicles (Lee, 1990), there is very little in applications to positioning tasks inside a distribution centre. It has been demonstrated that fuzzy control can provide stable control when the movement of the vehicle under consideration cannot be accurately modelled. This is of interest, since during autonomous operation, the dynamics of motion may change because of unforeseen changes in the environment or in the equipment. Fuzzy logic controllers are usually easier to design and modify, as they entail addition of rules or modification of membership functions, which are implemented in software.

TABLE 2.1 Research in intelligent control of material handling equipment .. (1)

Prototype Building	
* J.A.Sirgo et.al.(1990)	* Prototype of an automated warehousing and manufacturing plant in Oviedo University, Gijon, Spain.
Analytic modelling and network analysis	
* Junemann and Meister (1988) * Francis and White (1974), Berry (1968), Roberts and Reed (1972) * Kiran and Tansel (1989), Egbelu and Roy (1988), Gaskins et.al. (1989)	* A static model has been used to study warehousing systems at the Fraunhofer-Institute * Analytic modelling of particular dimensions of warehousing * Network analysis of resource utilization problems

TABLE 2.1 Research in intelligent control of material handling equipment .. (2)

Simulation of Warehouse Systems	
* Egbelu and Roy (1988), Linn and Wysk (1987), Chang et.al. (1986), Ozden (1988) and Kawabata et.al.(1985)	* Use of simulation to make predictions regarding the optimum use of warehousing facilities. Useful in designing a warehouse and in modifying operations and layout so as to improve productivity.
* Mansuri (1991)	* Addressed the problem of selecting storage in the warehouse and optimizing inventory relocation strategies in the warehouse
* Ruger (1990)	* Solutions to the problem of simulating large complex logistics systems.
*King, R. E. and Kim, K. S. (1995)	* Development of object oriented simulator AgvSim for AGV simulation.
*Caedarelli, G and Pelagagge, P.M. (1995)	* Simulation model able to represent both the handling and storage devices and the production process.

TABLE 2.1 Research in intelligent control of material handling equipment .. (3)

Mobile Manipulators	
* Horn et.al. (1992), Feng et.al. (1990), Dean et.al. (1990), Bruce and Davies (1991) and Knieremen and Puttkamer (1991) * Pomerbau et.al. (1991) and Garcia-Cerezo and Barriedo (1991) * Zimmer (1992) * Lee, P. H. and Wang, L. L.	* Electro-mechanical motion control system related to navigation * Stability of the control system and intelligent control * A method of representing the state of a non-linear system with a linear equation, which holds promise for simplifying the representation of large autonomous systems similar to the warehouse control system * AGV collision avoidance with fuzzy logic control
Sensor Application	
* Komoriya and Tani (1991), Tsudo and Yachida (1991), Yamaguchi et.al. (1992) and Romiti and Sorli (1992) * Zapata et.al. (1990), Donald and Jennings (1991), Egeland (1991), Komoriya and Tani (1991) and Wollnack and Schwill (1992) * Bak, D. J. (1995)	* New and modified sensor technology which have applications in material handling and robotics * Methods of interfacing the control system with different sensors in order to accomplish particular objectives * Automated navigation with AGV equipped with laser scanner

TABLE 2.1 Research in intelligent control of material handling equipment .. (4)

Large System Modelling	
* Zeigler and Chi (1991) * Badreddin (1991) and by Sowmya (1991) * Ruger (1990) * Kalashnikov (1991), Lee (1990), Troch et.al. (1992), Soloveva (1991), Luh and Zeigler (1991), Kozak (1992), Lunze (1992), and Wolstenholme (1992)	* Discrete event system modelling formalism * A formal description of the control structure for a mobile robot * Control logic modelling strategies * Large System modellingapplications
Discrete Event Control	
Dr. Yu Chi Ho (1989)	*Distinguished between human centered discrete event dynamic systems (DEDS) and continuous variable dynamic systems (CVDS). To quote: `Examples of the former are production or assembly lines, computer / communication networks, traffic systems, etc. where the evolution of the system in time depends on the complex interactions of the timing of various discrete events, such as the arrival or departure of a job...The "state" of such dynamic systems changes only at these discrete instants of time instead of continuously.'

TABLE 2.1 Research in intelligent control of material handling equipment .. (5)

AGV motion planning	
*Ganesharajah, T. and Sriskandarajah, C. (1995)	* Summary of research in the area of AGV scheduling, which involves issues such as AGV-conflict avoidance, AGV dispatching policies, and AGV routing.
Vision based AGV guidance	
* Cho, T H., Chang and H.K., 1995 * Baumgartner and Skaar	* Vision is used in material handling not only to identify targets, but also to extract information * Description of the theoretical development and experimental implementation of a complete navigation procedure for use in an autonomous mobile robot for structured environments.
Fuzzy Logic Control	
Lee, P. H. and Wang, L. L., 1994	* Fuzzy control of autonomous vehicles

3.0 MODELLING THE GOODS HANDLING PROCESS

Modelling man-made systems frequently uses discrete event modelling theory and a modelling framework based on system theory concepts. Several modelling formalisms (algebraic, differential equation, set theory) may be used to represent discrete event systems. The goods handling process, which is modelled as a discrete event process, is described in the following paragraph.

The goods distribution centre receives truckloads of palletized goods at the receiving docks. These pallets are then carried from the staging area, where they are deposited after being removed from the truck. The particular sub-system studied is described by the process of picking up pallet loads from the staging area at the unloading docks of a goods distribution centre and carrying them on an automated guided vehicle to a conveyor. To get a better understanding of how the system can be controlled and improved, it is necessary to account for the dynamic nature of the system, and to study its performance. As observed in the next section, simulation models meet these criterion.

3.1 Discrete event modelling

In his editorial,[1] Dr Yu-Chi Ho observed that discrete event modelling has come into existence to tackle the problem of modelling man-made discrete event systems. A majority of discrete event systems are dynamic, and models developed are classified as:

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[1] Proceedings of the IEEE, January 1989. Guest editorial "Dynamics of Discrete Event Systems"

	Timed	Untimed
Logical	Temporal Logic	* Finite State Machines * Petri Nets
Algebraic	Min-Max Algebra	* Finitely recursive process * Communicating sequential process
Performance	* Markov Chains * Queuing networks * Generalized semi-Markov process / simulation	

System simulation developed using system theoretic models (Zeigler, 1984) may use any of the above approaches for developing a model. The use of more than one formalism to represent the model is made necessary by the fact that many man-made systems are inherently "multi-facetted" (Zeigler, 1984), and cannot be adequately described with one formalism. The goods handling process modelled in this research can be put in the "Timed-Performance" category of model types, although the model comprises of sub-systems which are described by "continuous time" models and "min-max algebra."

An excerpt from "Multifaceted Modelling and Discrete Event simulation" by B.P. Zeigler provides a description of a simulator for a discrete event system. The underlying system theoretic model is represented in **Figure 3.1.**

A simulator for a discrete event process can be described by the following statements:

when receive an input (x,t):

done:=false

if $t_L \leq t \leq t_N$ then

$e:=t-t_L$	*increment elapsed time*
$s:=\delta_{ex}(s,e,x)$	*external state transition*
$t_L:=t$	
$t_N:=t_L+ta(s)$	
done:=true	

when receive an input (*,t):

done:=false

if $t=t_N$ then

$s:=\delta_{\phi}(s)$	*internal state transition*
$t_L:=t$	
$t_N:=t_L+ta(s)$	
done:=true	

S_M is a simulator for a discrete event system M, which has two state variables, one for the sequential state of M and the other for t_L, the time of the last event. The time for the next scheduled event is stored in storage cell "s". Cells "e" and "σ" hold the elapsed time and the time remaining respectively. Input "x" causes an external transition to the next state and increments the time for the last event by the time left in a particular state, ta(s) [ta(s)=Min{All the "time left" values of overlapping events}]. In the absence of "x", a synchronization signal results in an internal transition to a subsequent state.

3.2 Process modelling

The process `Carry pallet loads from staging to conveyor' subsequently referred to as [P], is carried out by an AGV. The actual network to be traversed by the AGV is shown in **Figure 3.2**, along with the lengths of the various links. The layout is deliberately chosen to be a very simple one, which, in fact, may not actually be used in a distribution centre. This is done to keep the analysis simple, and demonstrate the concept of "integrated control" discussed in the introduction. The layout can be extended to certain classes of larger, realistic AGV guidepath layouts, using a "building block" approach, as discussed in chapter 8. The AGV collects pallets from the unloading station corresponding to link 1 and moves to the conveyor along a fixed path. A schematic representation of an AGV used for carrying pallet loads from the staging area to a conveyor is presented in **Figure 3.3.** The AGV travels along the path described by the nodes of the loop: *Home _ 1 _ 2 _ 3 _ 4 _ Home*; as seen from **Figure 3.4**, and the pallet loads move along the path: *2 _ 3 _ 5*. Trucks carrying pallet loads arrive at the unloading dock and deposit 10 pallets, arranged in a single row. These are deposited on inclined rollers. Thus, pallets roll down the slope, on the rollers, due to gravity, and come to rest at a fixed stop, so that the distance separating the AGV track from the pallet is always fixed. Provision is made for lateral shift in the location of the pallet when using machine vision on the AGV. The location of the pallet is obtained by the AGV using a vision sensor. Once the pallet position is determined, the AGV is positioned directly in front and the forks, normally kept in the “low” position, are advanced until they move under the pallet. In case of interference, which is detected by forktip photoelectric sensors or load sensors, an error message is generated and communicated to a higher level of control for corrective action. This aspect of the process is not modelled. Once the forks are in place, the pallet is picked up, the forks are retracted, and the pallet is lowered on the “load platform” on the AGV. The AGV carries the pallet load to the conveyor. Since the location is known a-priori, the AGV deceleration and velocity are controlled to bring it to a stop at the correct location. The pallet is then picked up by the forks from the AGV load platform, the forks are extended and lowered in order to place the pallet on the conveyor. Subsequently, the AGV travels to a staging area and waits for the next load. If there is a pallet waiting, it travels directly to the unloading dock and repeats the “pick up-carry-deposit” operation.

The objective here is to model control of the AGV. This can be divided into 4 parts:

1. Determination of velocity profile of the AGV which satisfies dynamic constraints.

2. Devising a scheme for positioning the forklift while picking up a pallet load using vision feedback from a retroreflecting target and a single AGV mounted charge coupled device (ccd) camera.
3. Determining the performance of model free fuzzy logic based control of AGV velocity while positioning.
4. Modelling AGV control using the system modelling framework.

The process can be broken down into a sequence of events performed by different actuators. Thus, if the various states of the process {P} are represented by atomic events performed by the various actuators, where the underlying `state variable' is the extent of the process completed, it is possible to formulate a discrete event representation of the process. This approach is described in the following paragraph.

Discrete event based control of a process implies that (Zeigler, 1984):

1. The process is outfitted with finite state sensors which divide its state space into a finite output partition.
2. The process goes through a sequence of pre-determined states in response to signals from sensors.
3. Control signals are generated as each state boundary is crossed; i.e. at the completion of each atomic event. The control signal moves the process to a subsequent state boundary.

In order to determine the time `windows' for the events, it is necessary to estimate the minimum and maximum time for the atomic events which constitute the process. The time window corresponding to a particular event may differ depending on the input signal received. The time advance function, `ta', depends on both current state `q' and input `x'. Consequently, the time window is obtained as (Zeigler, 1984):

$$w_i = \max ta(S_i \_ S_{i+1}) - \min ta(S_i \_ S_{i+1})$$

The `control logic' using the discrete event specification or DEVS formalism can be determined after:

1. The time windows are calculated.
2. The sensors being monitored for input signals are identified.
3. The control action which will drive the process to the subsequent state-space boundary is determined.

The above mentioned steps are applied to the unloading process in a DC. The various atomic events along with the input signals and control actions are enumerated in **Table-3.1. Figure 3.5** exhibits the various states occupied by the process `unloading' and the state trajectory followed by the variable ζ indicating fraction of process completed. The entire process is divided into 7 states, and therefore ζ is a discrete variable which assumes values 1/7, 2/7, .., 1 at successive state boundary crossings. The outputs described can be broken down further, and it may be necessary to do so in order to provide a signal to activate various motors in the material handling equipment. The DEVS model outlined therefore acts in a supervisory capacity at a higher level of hierarchy as compared to the controllers for the actuators. An excellent discussion of this form of "Hierarchical Multi-component DEVS models" is found in Chapter 8 in the book "Multifaceted Modelling and Discrete Event Simulation" by B.P. Zeigler (Zeigler 1984).

3.2.1 Constrained AGVs motion

The time windows required for the atomic events described by AGV movement are functions of acceleration, deceleration and maximum AGV velocity. The motion during move and positioning operations is therefore subject to certain dynamic constraints, which are discussed briefly.

3.2.1.1 Velocity constraints

In order to move the AGV to the desired location as quickly as possible, the acceleration of the AGV and the speed while negotiating a curved path have to be controlled. Taking into consideration the maximum power, the friction resisting slip, the tendency to topple, and the maximum braking force, a velocity profile is generated by using Newton's laws of motion. The control logic (under the supervision of the AGV controller) indicates that "linear" and "curved" are the two path types considered. The flow diagram assumes a track, and steering is not considered. The movement of the AGV while positioning using vision feedback is performed at a comparatively low speed only.

For a given power and friction coefficient, an AGV is capable of accelerating and decelerating at a particular rate. Moreover, there is usually a limit for the maximum velocity at which an AGV is permitted to travel. The maximum acceleration is determined by the available torque. However, if the force supplied is greater than the limiting friction force, the maximum acceleration depends on the available friction coefficient. The maximum deceleration, likewise, is determined by friction (when the wheels are locked), or maximum torque, if braking is accomplished under power. The situation is more complicated when the vehicle is negotiating a curve, and we assume a constant velocity which does not result in toppling or sliding.

The motion of the AGV is modelled using Newton's laws of motion, and conservation of energy [kinetic energy dissipated by friction work].

3.2.1.2 Vision based positioning

The AGV is equipped with a ccd camera which images a retro-reflecting target. The accuracy of locating the pallet determines the time and the maneuvering required to position the fork under the pallet. The pallet position in the staging area is assumed to be fixed with respect to the perpendicular distance from the AGV track, since this can be ensured by using a mechanical stop during the unloading process. The location of the pallet in the direction of travel of the AGV can vary, and is not known a-priori. Consequently, the AGV has to sense this distance before any positioning move. The AGV is assumed to be in motion while imaging the target, and there is chance of error in the distance readings. By modelling this error as a random normal probability distribution, a model was built up, and positioning control was simulated.

3.2.2 Process model flowchart

The process [P] has been described in terms of a set of discrete events. A schematic representation of the process is provided in **Figure 3.6a..c.** While a hierarchical structure is assumed for the overall process control, each of the event controllers function autonomously. External events act only as triggers which alter the course of internal events.

The model depicted provides a description which can be employed to devise an intelligent controller for the process [P]. The objective here is more limited, namely, study the performance {time for process & AGV utilization} of the system under varying conditions of AGV motion, the factors of interest are the time needed to traverse the distance between the staging area and the conveyor, and the influence of parameters like track friction, available power and positioning control. The model discussed is abstracted further before simulation by considering only AGV acceleration/deceleration, and the influence of positioning control on AGV velocity during positioning. The sensors of interest are a) AGV drive wheel velocity sensor and b) ccd camera for supplying vision data. A positioning controller is inserted in the position of drive wheel (actuator) controller. Three cases; a) Fuzzy control, b) Model following control and c) No control are compared.

TABLE-3.1 Atomic events along with the input signals and control actions for the process `unloading.'

No :	Event	Input(s)	Control action
i	Move AGV fork under pallet.	1. Pallet position (correct / incorrect).	Move forward a predetermined distance / output error signal.
ii	Raise fork with load.	1. Fork with pallet (Y/N).	Raise fork `h_1.' /output error.
iii	Carry pallet to conveyor.	1. Fork with pallet (Y/N). 2. Conveyor free (Y/N).	Move AGV to conveyor station and follow AGV track / output error.
iv	Lower pallet on conveyor.	1. Conveyor stationary (Y/N). 2. Fork position accurate (Y/N).	Lower fork height by `h_2.' / output error.
v	Return AGV to `home'.	1. Pallet off the fork (Y/N).	Move to `home.'
vi	Move pallet to end of conveyor.	1. Pallet on `incoming' end (Y/N). 2. No pallet on `outgoing' end.	Engage conveyor drive and move pallet load to opposite end.

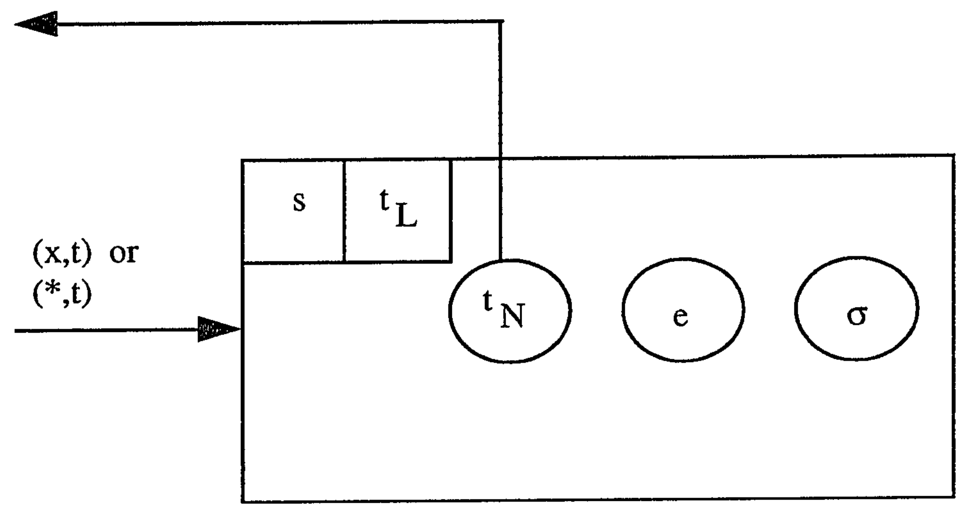
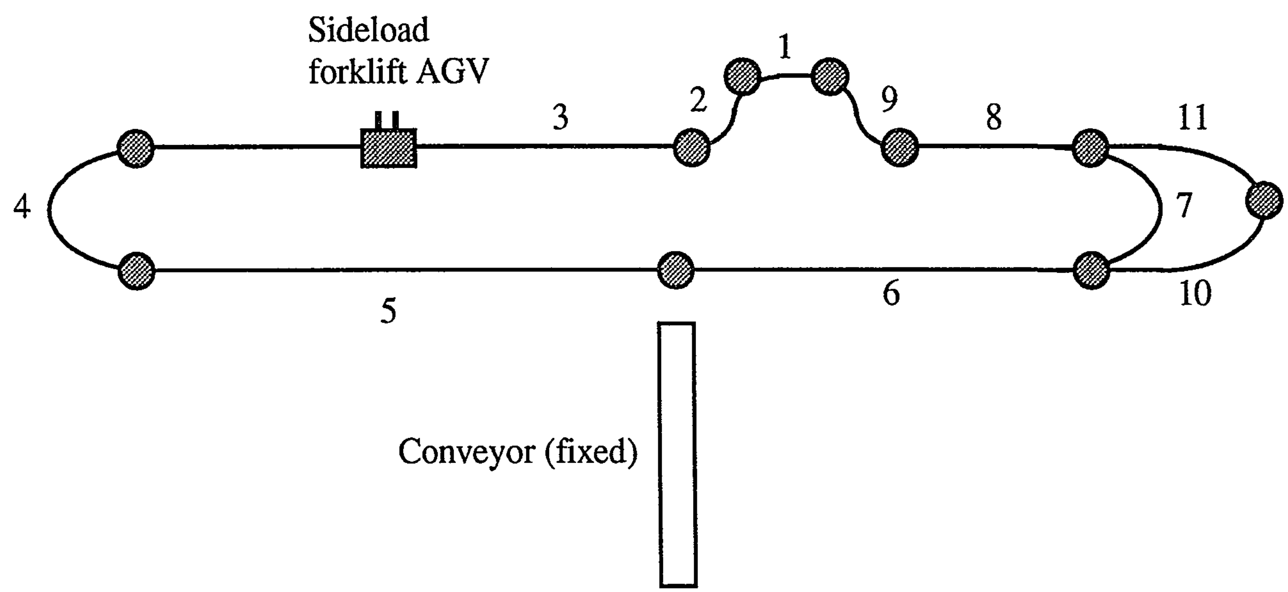
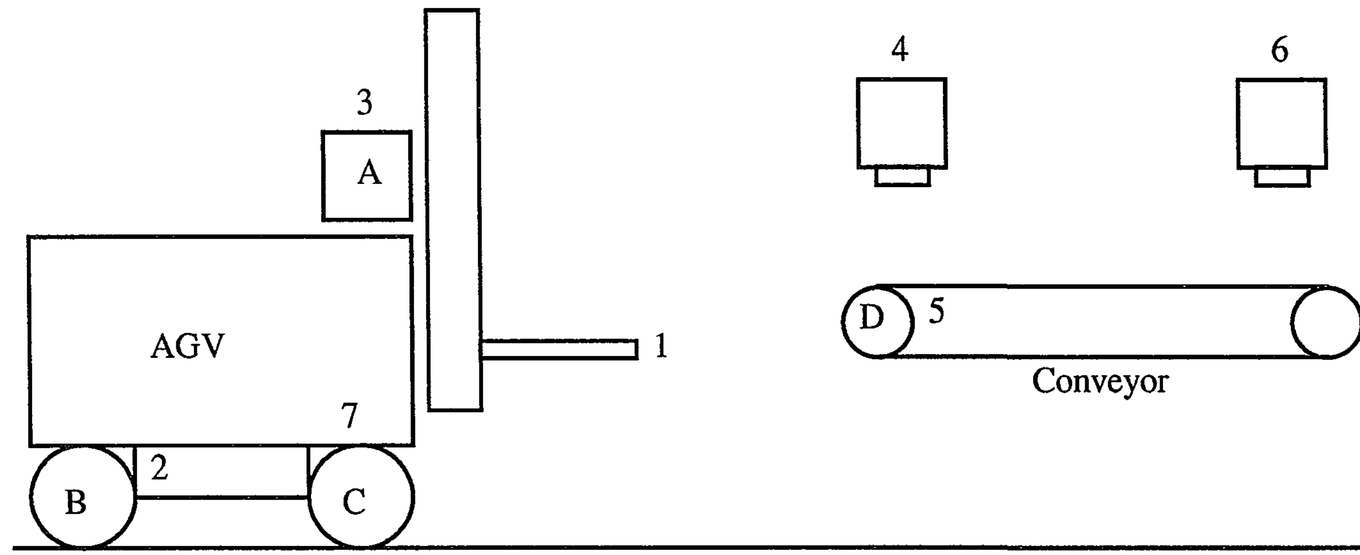


Figure 3.1 Simulator for a discrete event system



Link #	1	2	3	4	5	6	7	8	9	10	11
Length (m)	4	4	25	5	21	21	5	8	4	4	4

Figure 3.2 Schematic of AGV path



Sensors: 1..7
Actuators: A..D

System attributes sensed
1 Pallet height
2 AGV track
3 Weight of pallet load
4 Presence/absence of goods
5 Conveyor velocity
6 Presence/absence of goods
7 Velocity of drive wheel

Actuator functions
A Fork up/down
B AGV drive
C AGV steering
D Conveyor drive

Figure 3.3 Schematic of material handling equipment

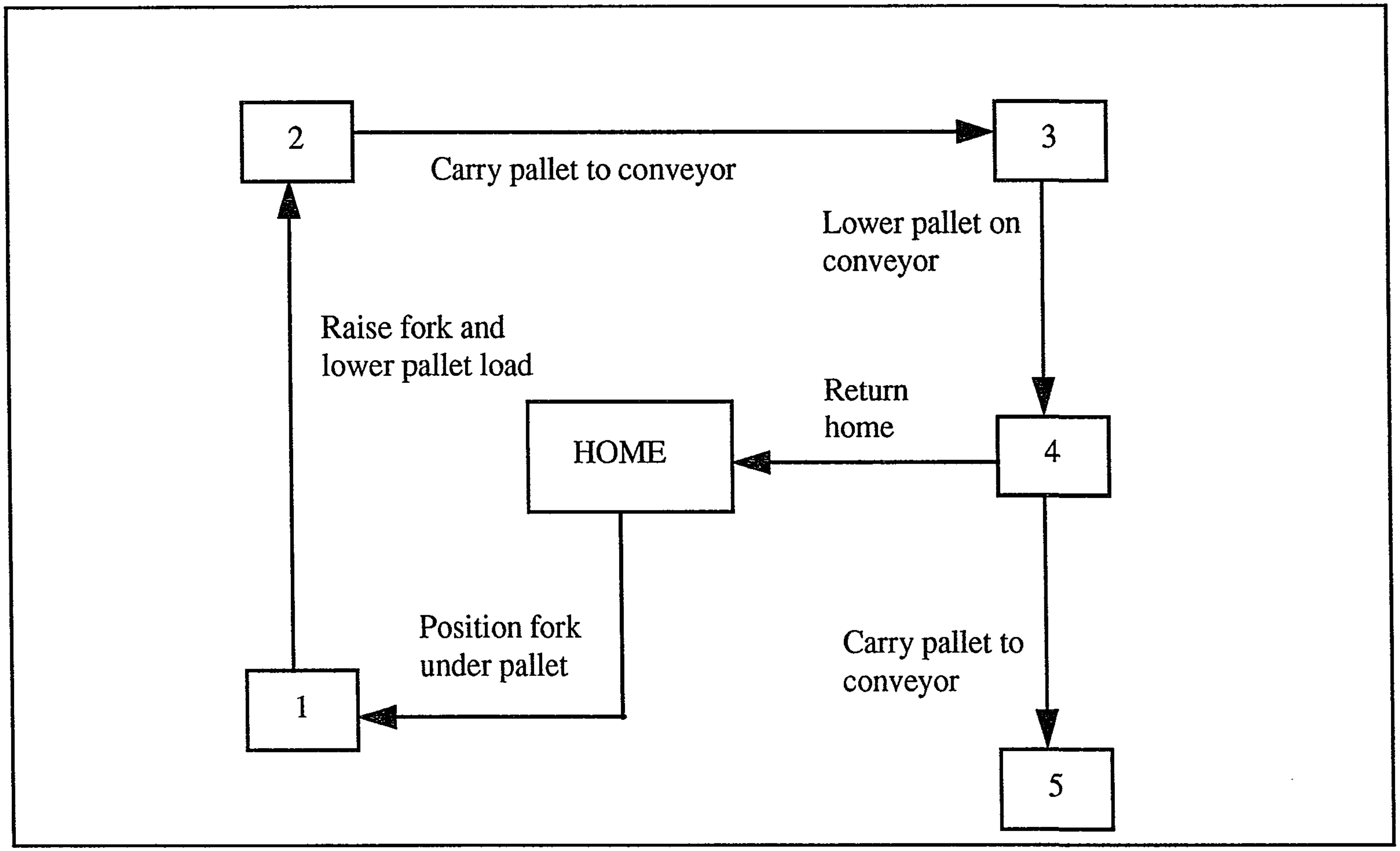


Figure 3.4 The process [P] described as a sequence of events

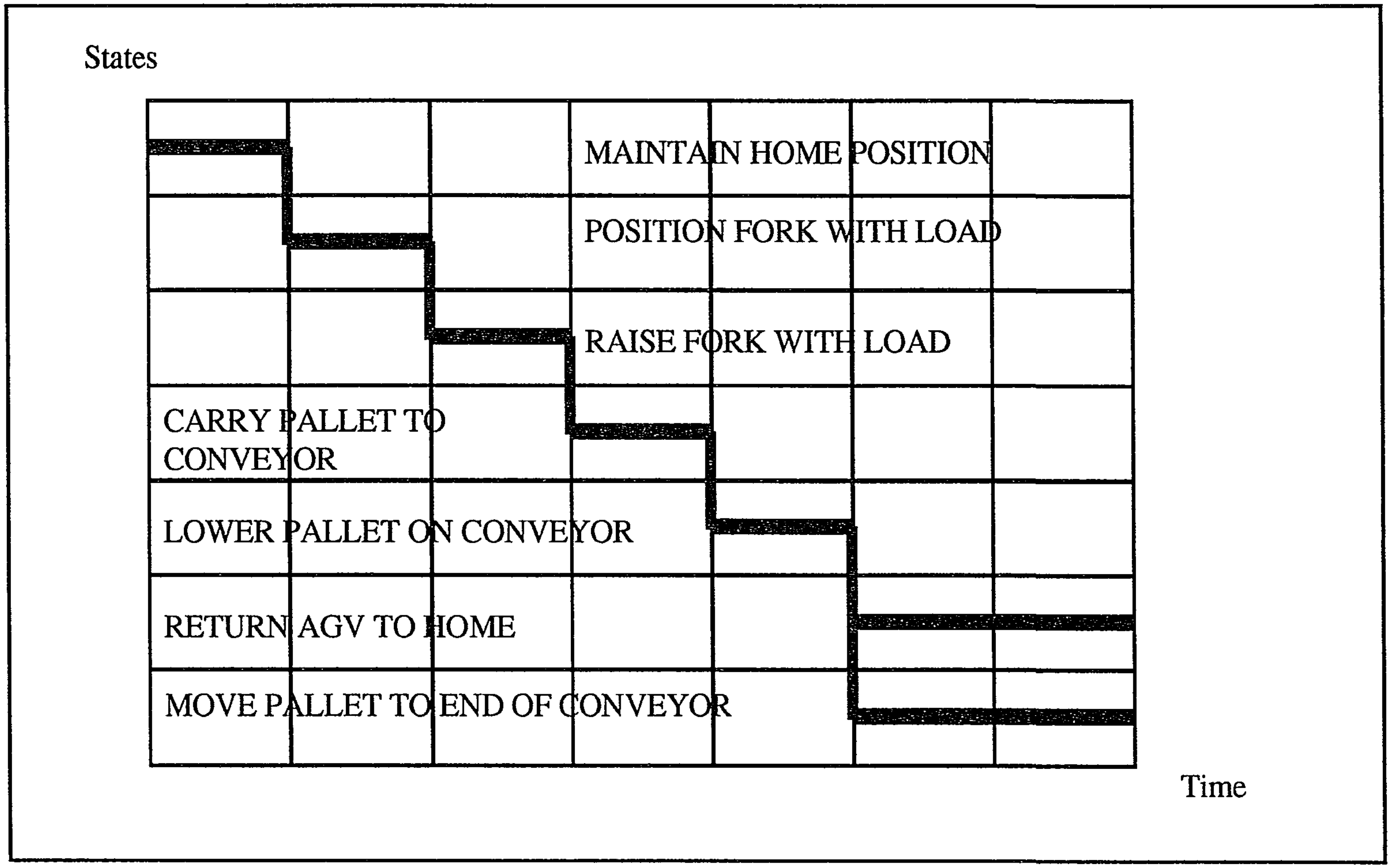


Figure 3.5 State trajectory of the process [P]

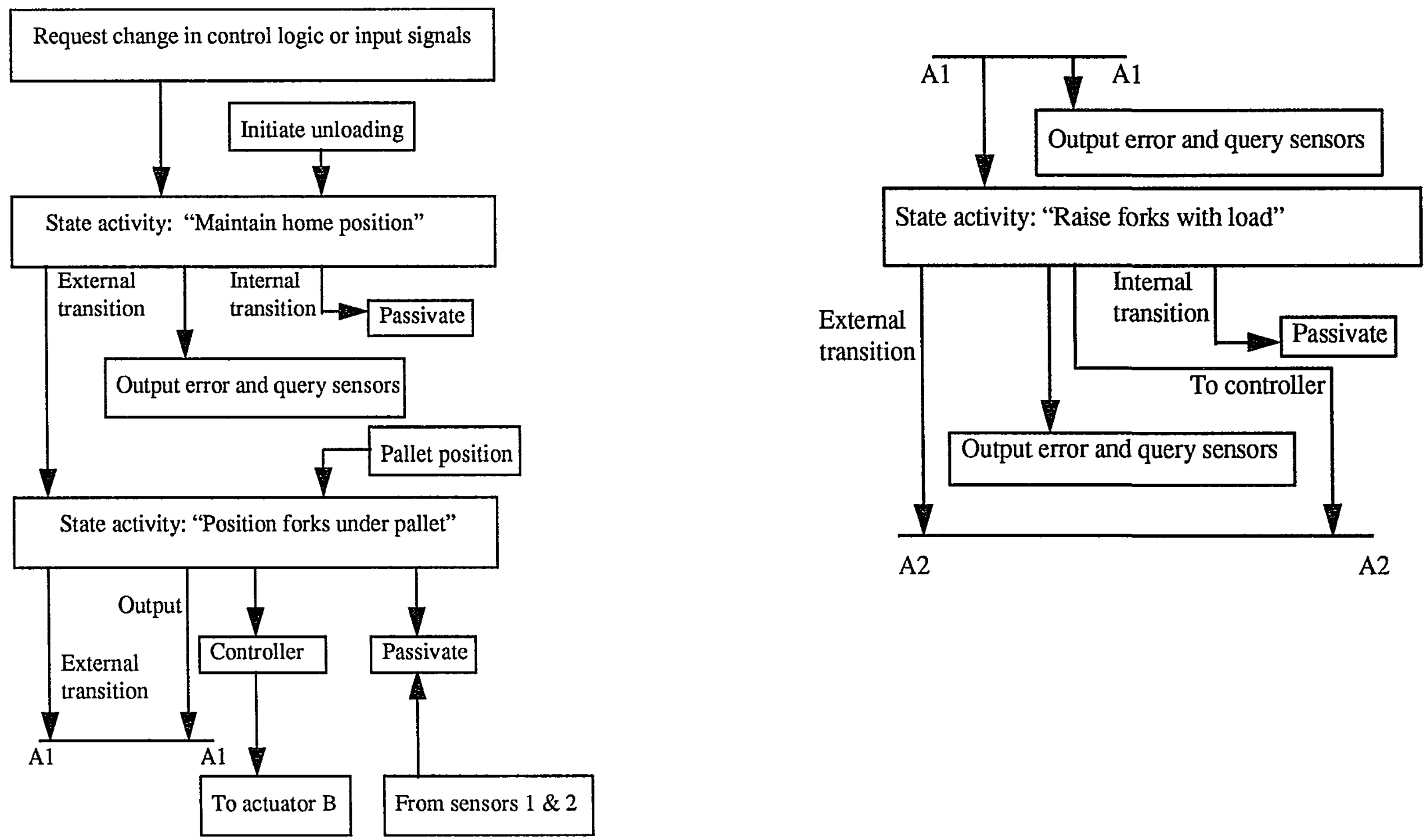


Figure 3.6a Overall discrete event representation of control logic

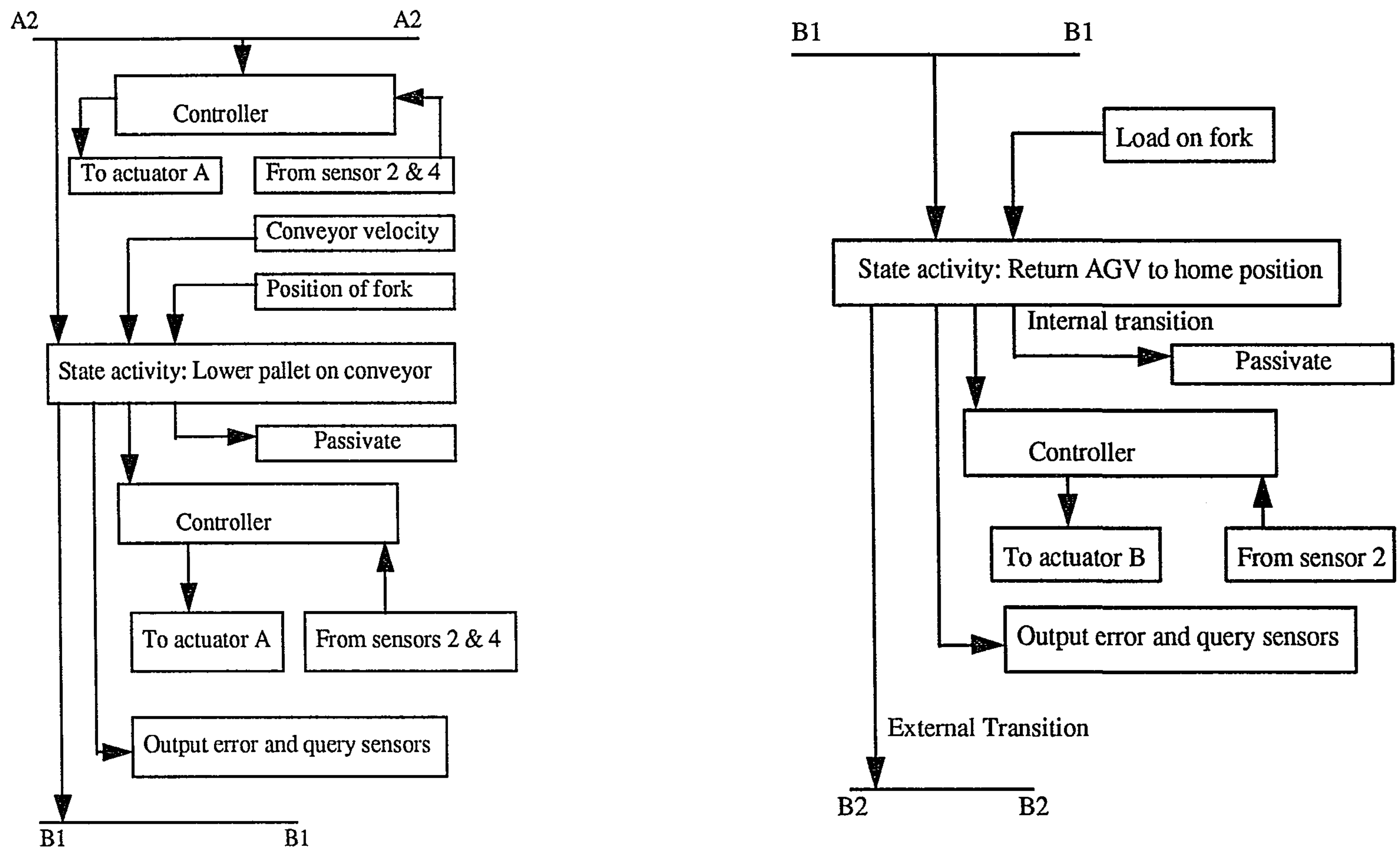


Figure 3.6b Overall discrete event representation of control logic

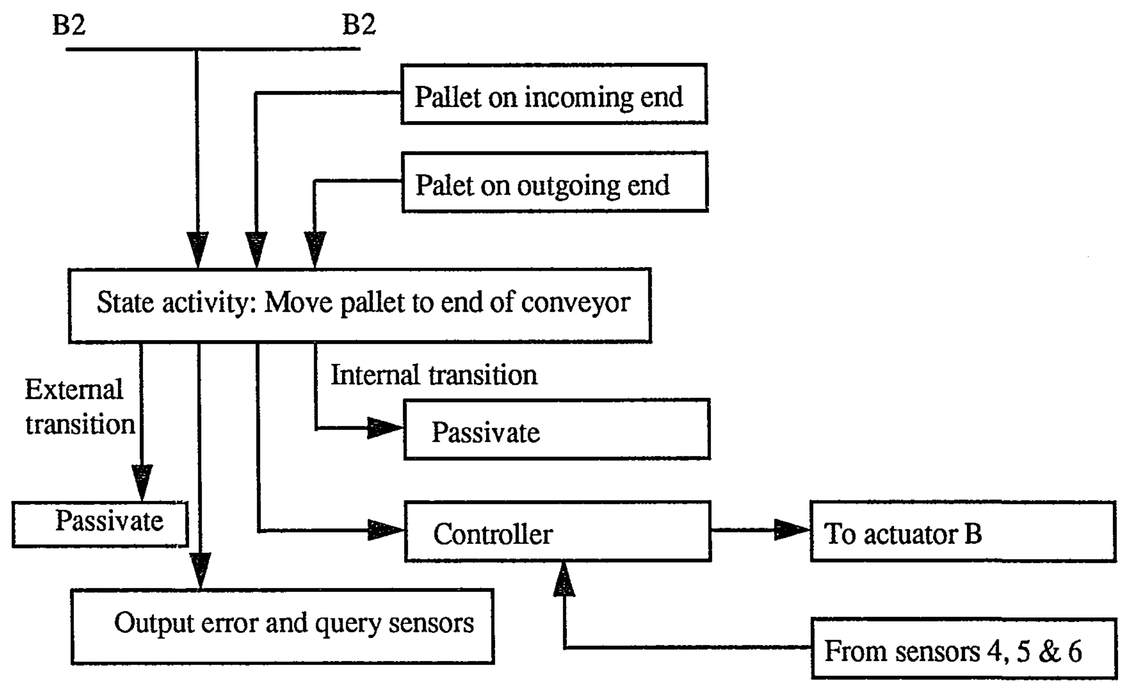


Figure 3.6c Overall discrete event representation of control logic

4.0 AGV VELOCITY PROFILES

In order to move the AGV to the desired location as quickly as possible, the acceleration of the AGV and its speed while negotiating a linear or curved path have to be controlled. In addition to available torque, slipping and toppling tendencies constrain the maximum velocity and acceleration of an AGV. Thus, for a given power and friction coefficient, an AGV is capable of accelerating and decelerating at a particular rate. There is usually a limit for the maximum velocity at which an AGV is permitted to travel. The maximum acceleration is determined by the available torque. However, if the force supplied is greater than the limiting friction force, the maximum acceleration depends on the available friction coefficient. The maximum deceleration, likewise, is determined by friction. In most cases, however, deceleration of the AGV is carried out under power, and is therefore torque limited. Toppling over is a constraint which comes into play when the AGV is negotiating a curved path. The AGV is assumed to be stable when accelerating or decelerating along a straight path, and toppling does not occur in the direction of travel.

This friction dependent linear velocity profile is depicted in **Figure 4.1.** It is clear that when there is significant difference between the maximum and the minimum velocity, there is a region beyond which the AGV will slip if the acceleration is limited by friction. If the acceleration is limited by the available torque, the region beyond the curve is 'infeasible.' Provided that sufficient power is available, the velocity profile traced by the AGV as it covers a particular distance shows some interesting trends. At low values of the coefficient of friction, the maximum velocity permitted may not be attained because of the excessive amount of time required during accelerating and decelerating. The plot of velocity as a function of distance is generated using the friction independent relation: $\{v_2\}^2 = \{v_1\}^2 + 2\ a\ \Delta s$, where '$v_1$' and '$v_2$' are the initial and final velocities of the AGV respectively, 'a' is the acceleration and 'Δs' is the distance covered. The acceleration depends on the torque supplied, and is found as a function of the torque available, from the relation; a = force / mass of AGV, where 'force' is the ratio of the torque and the drive wheel radius. If the drive motor in the AGV is capable of causing acceleration exceeding μ g, the actual acceleration becomes friction dependent. A typical value of μ=0.8 for the coefficient of friction between rubber and steel gives us a maximum friction limited acceleration of 7.84 m/s^2, where 'g', the acceleration due to gravity, is assumed to be 9.81 m/s^2.

The velocity profile during maximum deceleration of the AGV may be modelled with the equation relating kinetic energy loss [$m(v_2^2 - v_1^2)$], to energy lost through work done due to friction [μ g m Δs]: The resulting equation is $\{v_2\}^2 - \{v_1\}^2 = 2\ g\ \mu\ \Delta s$, since the mass of the AGV, m, cancels out. This equation gives the velocity profile as a function of distance travelled when the vehicle is sliding to a stop, or braking gently when the coefficient of friction is low. If sufficient torque is not available to take advantage of higher friction coefficients, the AGV will accelerate slowly, but may be able to decelerate rapidly, as the maximum limit to deceleration is only friction. When the wheels are locked, the maximum deceleration is limited by the coefficient of dynamic friction, which is lower than the coefficient of static friction. Antilock braking control can therefore be used to increase the maximum possible deceleration. In the material handling process modelled, the AGV is assumed to accelerate and decelerate under power, and the available torque provides the values of maximum acceleration and deceleration.

When the vehicle is negotiating a curve, centrifugal forces tend to topple the vehicle on its side. If the AGV accelerates through the curve, the maximum velocity is limited by the two constraints of sliding and toppling. If it is assumed that the AGV negotiates curves at a constant velocity which does not result in toppling or sliding, the velocity is constrained by the tendency to topple, and to slide radially. The coefficient of friction between the tracks and the wheel, μ, limits the maximum velocity. At low values of μ the maximum velocity at which the AGV may travel without slipping increases with rising μ, but beyond a certain point, the tendency to topple limits the velocity. The maximum permissible velocity also increases with increasing turning radius.

4.1 Effect of power and friction on AGV linear velocity profile

Let τ be the maximum torque of which the AGV prime mover is capable. The force available for acceleration is therefore given by τ/r_w, where r_w is the radius of the drive wheel. The torque limited acceleration of the AGV is given by $a_\tau=\tau/(r_w m_{AGV})$ where m_{AGV} is the mass of the AGV. This relation is valid only if the coefficient of friction of the AGV track is such that the AGV does not slip when the torque reaches its maximum value. Thus, for linear movement,

$a_\tau = \tau/r_w m_{AGV}$, and $a_{fric} = \mu g$

a_{max} = maximum (a_τ, a_{fric})

Here,

τ =maximum available torque at the drive wheel

r_w =radius of drive wheel

μ =coefficient of friction between track and wheel

a_{max} =maximum acceleration of AGV

a_{fric} =friction limited acceleration

a_τ =torque limited acceleration

m_{AGV} =mass of AGV

As discussed previously, the maximum possible linear deceleration is equal to a_{fric}. In the process modelled, deceleration is assumed to take place under power, and therefore the maximum deceleration is equal to the maximum acceleration.

4.2 Velocity constraints while moving around a curve

For curved path motion the total acceleration is the vector sum of the normal and tangential components of acceleration. Thus, $\{a_{curved}\}^2 = \{a_{normal}\}^2 + \{a_{tangentiall}\}^2$. The two components of acceleration are given by: $a = R\,\omega^2$ and $a_{tangential} = R\,\alpha$. Here, 'a' is the normal or tangential acceleration, 'α' is the angular acceleration, 'R' is the radius of curvature of the curved path, and ω is the initial angular velocity.

In general, curved paths have to be negotiated at much lower velocities as compared to linear paths, and no significant savings in time of travel can be expected when the curve radius is small, as is generally the case. While linear velocity is constrained primarily by slippage, radial motion has a toppling constraint as well. This will limit the maximum velocity around a curve, particularly when the centre of gravity of the AGV is comparatively high. In the material handling process model it is assumed that the tangential velocity remains constant while the AGV negotiates a curved path. Therefore, $\alpha=0$ and the tangential component of acceleration drops out.

The major velocity constraint for an AGV negotiating a bend is the one which guards against toppling. The height of the c.g. of the AGV typically would lie between 1m and 1.5m. Toppling over occurs when

$$m\,g\,WB = 2\,m\,v^2_{tangential}\,h / r_{curve}$$

where 'WB' is the wheelbase and 'h' is the height of the centre of gravity of the AGV from the floor, m=mass of the AGV with load and 'g' is the acceleration due to gravity. When friction is low, the AGV velocity is friction limited; as friction increases, the tendency to topple may limit the velocity if the cg of the AGV is sufficiently high.

4.3 Plots of constrained AGV velocity

Linear and curved path velocity profiles of a typical sideload forklift AGV, taking into account the friction and power constraint to acceleration are plotted for the following data:

Maximum payload	=1364 Kg
Power	=15 kW at an AGV velocity of 4m/s
r_w	=0.1 m
μ	=Range 0.2 to 0.8
WB	=1.257 m
h	=1.5 m
m_{AGV}	=2633 Kg (Total AGV mass)
R	=Range 0.001 to 10 m

Figure 4.2 demonstrates the effect of friction on the maximum velocity while navigating a curve of radius R where the maximum velocity is limited by the friction coefficient and the tendency to topple. Individual toppling and friction governed plots, and a plot of the maximum feasible velocity taking these into account are included in the Appendix (**Figures B-2 & B-3).**

A rise in the maximum linear velocity is observed as the friction coefficient rises from 0.2 to 0.8 in steps of 0.2, as shown in **Figure 4.3.** The effect of changing the available power is examined in **Figure 4.4.** The graphs reveal how the linear velocity profile would be altered if the available power is changed. The velocity profiles are strongly influenced by distance travelled, when there is a comparatively large velocity change. This is clear from the velocity profiles plotted in **Figure 4.5** for linear distances of 1,2,3 and 4 m travelled by the AGV. The acceleration is due to available power of 15 kW. The commercially available AGV under study normally travels at certain discrete speeds only, and is not capable of following a velocity profile without a controller. Positioning is effected at a 'creep' velocity. The torque available is quite low, and acceleration is usually torque limited. The comparison of the velocity profiles presented in **Figure 4.6** obtained from the specified velocities of 0.5, 0.75 and 1.0 m/s for the AGV, and the torque limited velocities which are possible.

The need for friction sensitive movement applies during AGV deceleration, which is limited by friction. The velocity while going around a curve is limited by friction and by the tendency to topple, For small radii of curvature, the AGV slips easily along the normal direction of travel. This happens when:

$$m * g * \mu \leq m * v^2_{tangential} / R \quad \text{or } v_{tangential} \geq \sqrt{\mu g R}$$

At high values of μ, the tendency to topple could limit the tangential velocity when the c.g. is relatively high. The AGV velocity profiles plotted as a function of the height of the c.g. are presented in **Figure 4.7.** The tendency to topple over increases with the height of the c.g. The reverse is true when the wheelbase increases, and the maximum velocity is more likely to be limited by the friction coefficient. The power of the drive motor affects the acceleration of the AGV. Of course, it is necessary to specify at what velocity the torque is determined. Assuming that the drive wheels are powered by a 15kW motor rated for an AGV velocity of 4 m/s,, the acceleration of the AGV without load works out to be 1.42 m/s^2. **Figures 4.8a** and **4.8b** demonstrate graphically the variation of torque with power and velocity, and the AGV acceleration corresponding to torque. The graphs are developed with the relations: torque=power/angular velocity, and acceleration=torque/(mass* wheel radius).

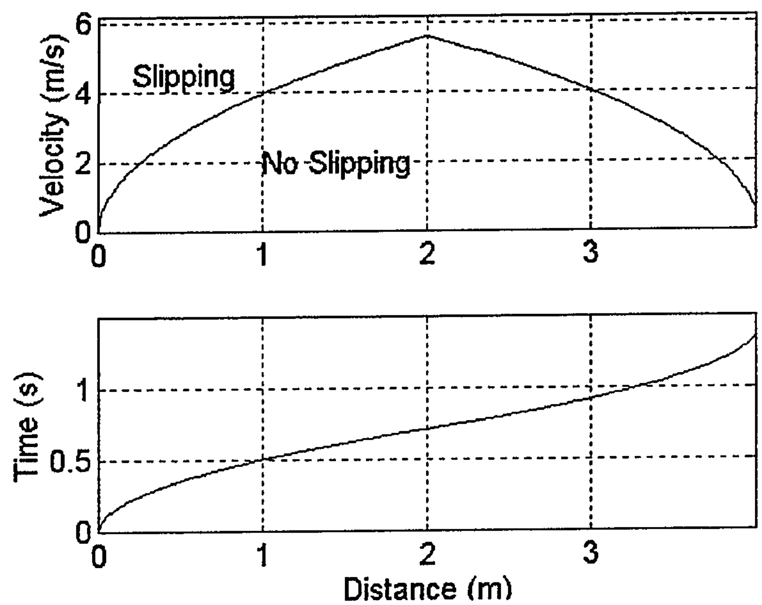


Figure 4.1 Friction dependent linear velocity profile

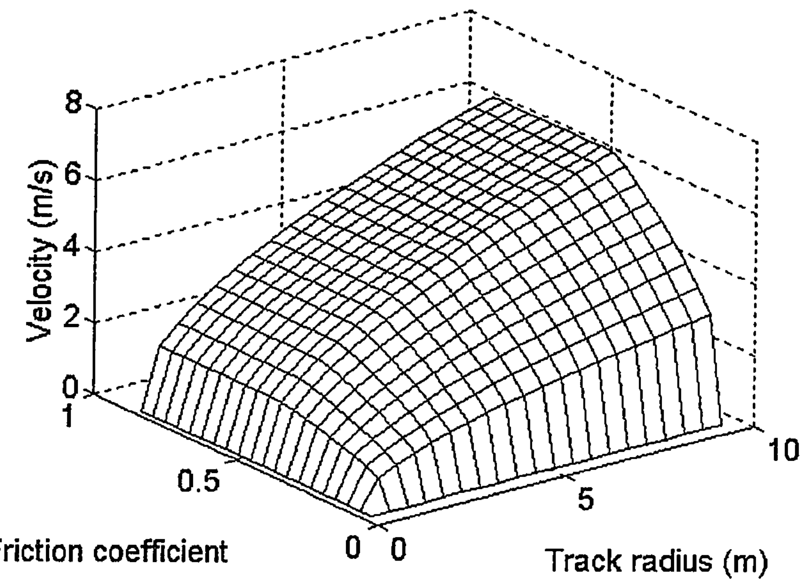


Figure 4.2 Effect of friction and turn radius on AGV velocity profile

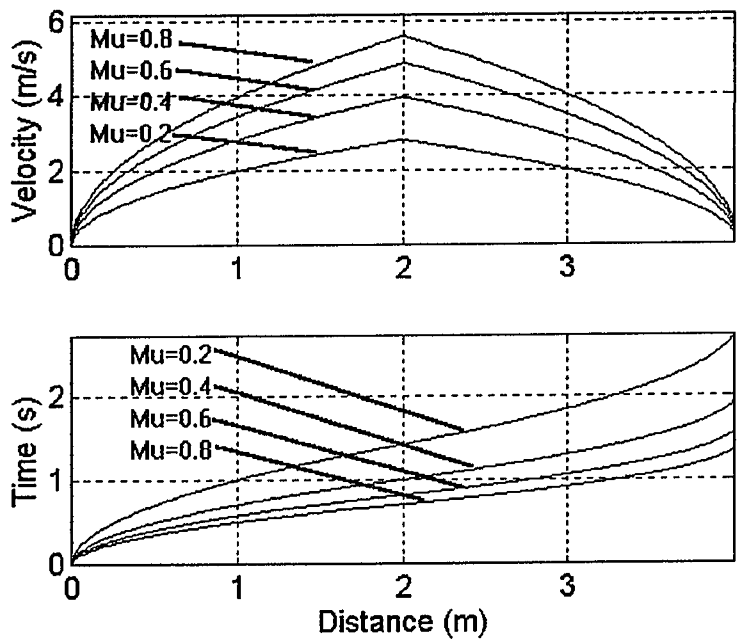


Figure 4.3 Effect of changing the friction coefficient on the linear velocity profile. {"Mu"=μ, the coefficient of friction}.

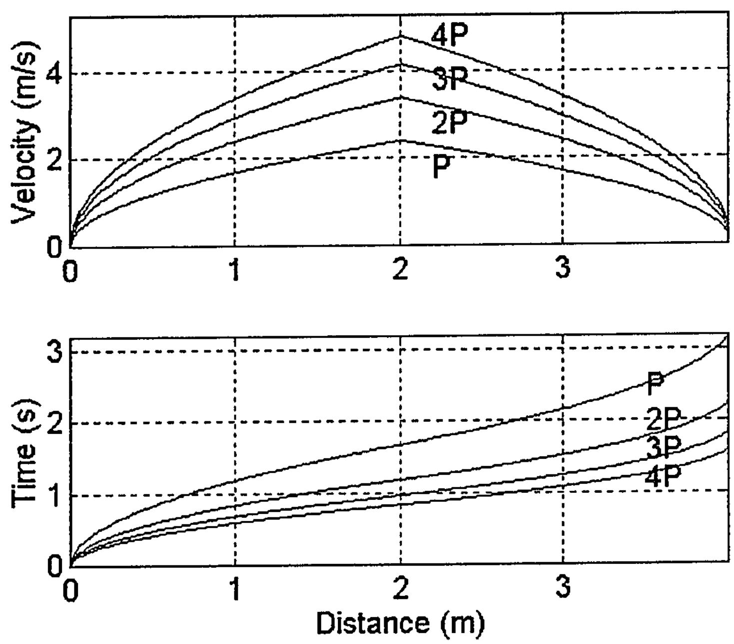


Figure 4.4 Effect of changing available power on the linear velocity profile

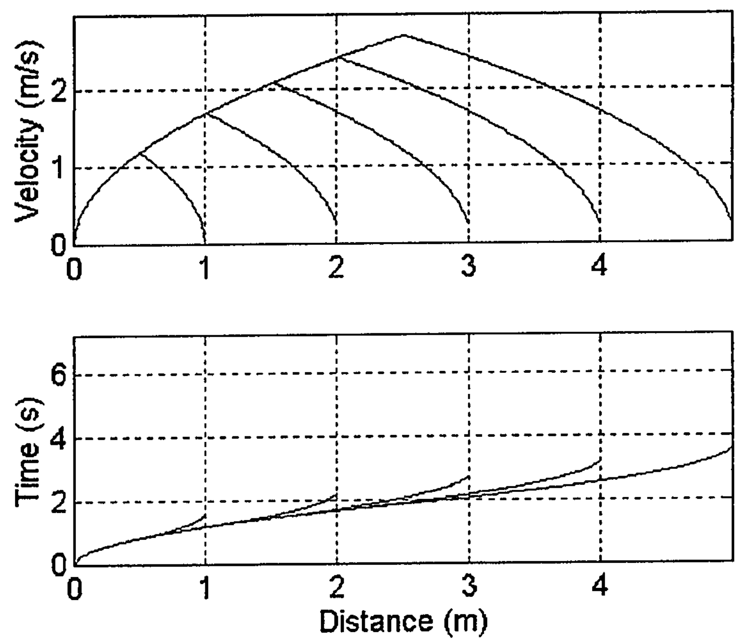


Figure 4.5 AGV velocity profile as a function of total distance travelled

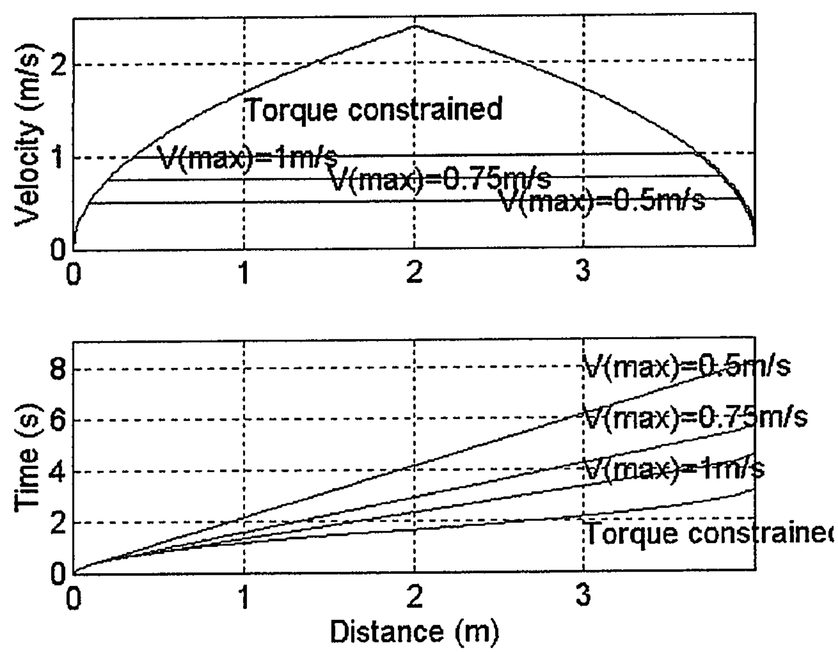


Figure 4.6 Comparison of power limited and commercial AGV velocity profiles

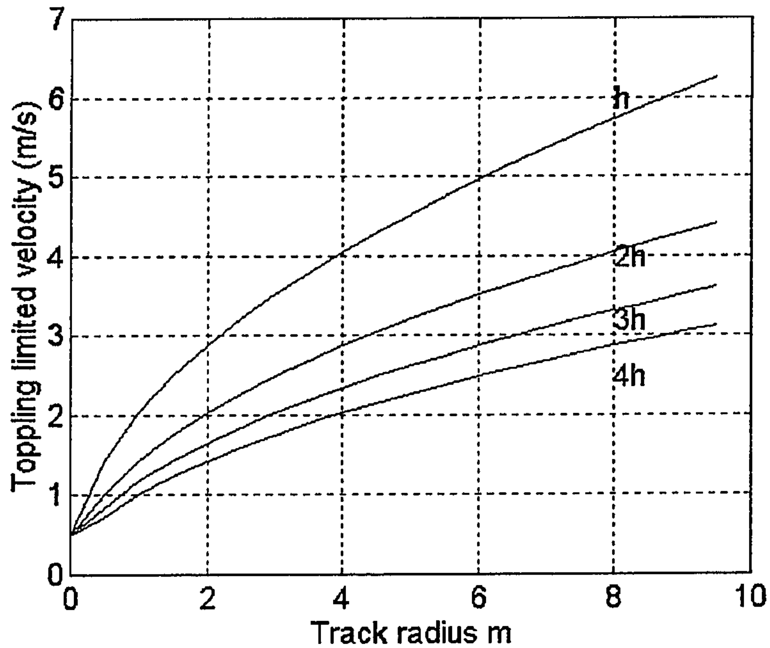


Figure 4.7 Influence of height of c.g. on maximum AGV velocity along a curved path

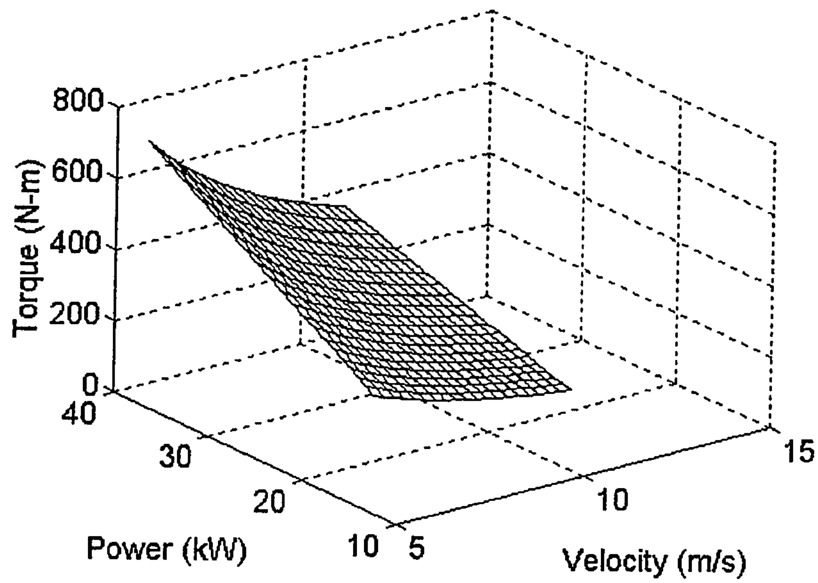


Figure 4.8a Variation of AGV torque with power and velocity

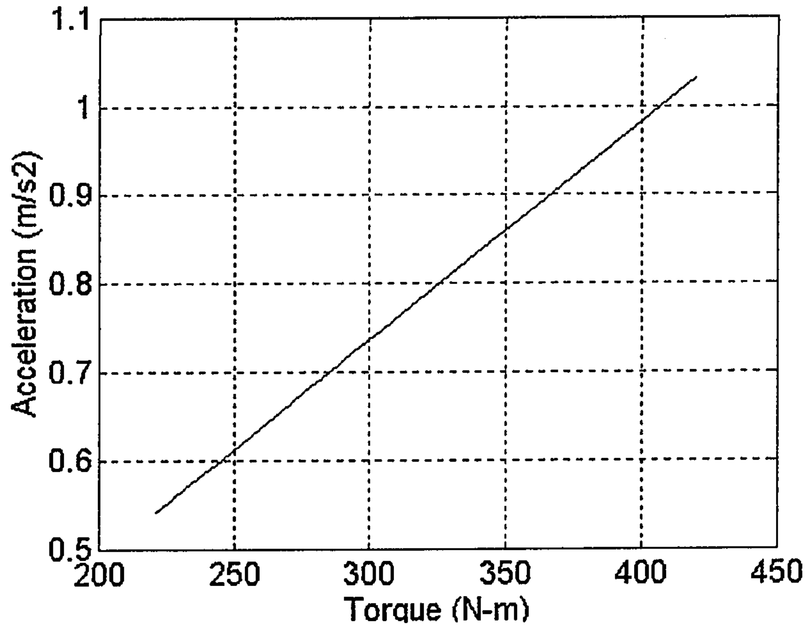


Figure 4.8b AGV acceleration corresponding to torque available at drive wheel

5.0 AGV POSITIONING USING VISUAL FEEDBACK

5.1 Problem description

In modelling the process of automatically picking up pallet loads from the staging area and carrying them to a conveyor, it is necessary to model AGV positioning in front of the pallet to be picked up. This task of automatically picking up pallets with a sideload forklift AGV can be complicated if the exact position of pallets is not known. This is highly probable, given the physical situation at the receiving docks in a goods distribution centre, where pallet loads from trailer trucks are unloaded and deposited in a staging area. The forklift therefore has to be guided to the correct position by using sensors. Assuming that the approximate pallet location is known (to within one pallet length), and the pallet orientation does not vary excessively on unloading, vision based positioning can be employed to guide the forklift to the correct location. Machine vision sensing is superior to using mechanical sensors when it comes to reliability, an important issue in a "lights out" environment, because it is non-contact sensing, and damage or wearing out of sensors due to repeated contact or collision is not an issue. Furthermore, a significant saving in time is possible when using machine vision sensing, since the AGV can be guided to the target at a high velocity, coming to a stop with optimum deceleration. Mechanical sensors necessitate "creep feed positioning", usually at 0.1 m/s or less, and a significant increase in time required to carry out the process results. The proposed approach is discussed next, prior to modelling the positioning method and testing its performance.

5.1.1 Setup for vision-based positioning

An AGV equipped with a ccd camera images a retro-reflecting target on the pallet when it approaches the staging area. The pallets are fitted with the retro-reflecting target, which is fixed in a recess in front of the pallet. The targets would be fixed while manufacturing these special pallets.Typical pallet openings which accomodate the forklift forks have a compliance of 2.5 cm, while the machine vision provides positioning accuracy of 1 cm. Skew in positioning the target can be tolerated as well, since the target position is retrieved by calculating the co ordinates of the target centre, as discussed later. The image has to be retrieved and processed, and the use of a retroreflecting target[1] speeds up the image processing since, by exploiting the high contrast achieved by using such a target, binary image retrieval is conveniently carried out by intensity thresholding. The offset of the image provides information regarding the position of the pallet. The pallet position and the target offset is depicted in **Figure 5.1.**

The accuracy with which the vision system calculates target position determines whether it is possible to use this visual positioning method. In order to examine the accuracy of locating a target from image data, a rectangular target made from a retroreflecting screen has been imaged with a video digitizer. The experiment was carried out under conditions of ambient lighting, with a white lamp mounted next to the camera lens. The retrieved image is processed to obtain the position of the pallet with respect to the camera, in the direction of travel of the AGV.

5.2 Experimental determination of positioning accuracy

A retroreflecting target, consisting of glass beads on paper was imaged by a ccd camera ('Cohu' ccd camera with 754 × 488 pixels on the semiconductor imaging surface) equipped

[1] Product marketed by 3M Co.

with a 50mm diameter short focal length lens (12.5 mm) and a point source of white light. A 2×4 cm retroreflecting target was positioned at a distance of 125 mm from the camera. An aperture of f/16 was found adequate for capturing the image. The target was offset from the centre of the camera in 2 inch (50mm) intervals. A view of the ccd camera equipped with a point source of light is shown in **Figure 5.2.** The set-up is utilized to acquire data of the target image, which was digitized (using a digitizer board from PCEyes with a resolution of 640 × 480 pixels, and a personal computer). The image files (raw data) were read with MATLAB[2] and stored as matrices. Since these files were excessively large in size (640 x 480 pixels, with 64 levels of gray scale), they were reduced in size by a factor of 2 prior to further processing. The role of a retroreflector is the key to successfully controlling AGV positioning with a high degree of reliability. A comparison (visual) of the intensity of the images produced by a retroreflector with that produced by a white surface dramatically emphasises the advantage. The dark rectangle to the left of **Figure 5.3** is white paper illuminated, like the retroreflector on the right, by a point white light source. Imaging a typical pallet would provide even less contrast than the white paper.

Binary images were obtained by thresholding the intensity matrices (64 gray levels) at a value of 55. {The value of 55 gray level was arrived at from a visual inspection of the raw image data. The background reflection was clearly quite low in intensity, and a trial-and-error approach yielded the approximate threshold intensity}. T his resulted in a 0/1 matrix. To obtain the centre of gravity of the image, moments were obtained from the left axis of the binary matrix, and the quotient of the moment and the area was calculated. This procedure is outlined in **Figure 5.4,** which is a flow chart of the steps followed in calculating the target location. The x coordinate of the target is equal to Σ xdA / A.

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[2] Numeric computation and visualization software from 'The Mathworks Inc.'

where 'x' is the pixel distance from the left edge of the image, and dA is the associated area (unity for one pixel).

An alternative method of reading the first and last occurrence of a 'high' value may have provided an approximate image location very rapidly, but can give very erroneous results in case a small reflection at some location other than the target caused a few pixels to go high. The method of calculating moments ensures that the effect of very small areas of high reflection does not affect the computed centre of gravity very drastically.

Experimental results indicate excellent agreement of the measured offset with the values obtained from image files. Some 'glare' and intensity variation was observed when the target position was altered, and the area of the binary image varied to some extent. The centre of gravity, however, was not significantly affected, since the target size is small compared to the field of view. The distance of the image centre of gravity (in pixels) is plotted as a function of the measured distance (cm) in **Figure 5.5.** Results show that the x axis coordinate of the target can be determined correct to ±5 mm,(which is the maximum difference between the experimental readings and the computed distance from the ccd image). This is sufficient resolution to guide the AGV.

5.2.1 Application of experimental results to commercial AGV

From the results it is clear that a ccd camera imaging a retroreflecting target is a viable means of determining target offset, with image processing (intensity thresholding and moment calculations). AGV track layout requirements for positioning a commercial sideload forklift AGV can be obtained from a knowledge of the target offset which can be imaged an the field of view of the ccd camera. The data can be used to compute the deceleration required to bring the AGV to a stop in front of the pallet. The required deceleration is a function of the initial speed of the AGV and the offset distance, as observed from **Figure 5.6.** The maximum allowed offset distance is a function of the axial distance of the ccd camera from the pallet, the lens diameter and the focal length of the lens used. For a typical wide angle lens (f<17mm)[3], a 100 degree field of view can be obtained. Therefore, an offset of 3.57 m can be imaged conveniently when the axial distance of the camera from the target is 3 m. This number for the offset distance is approximately equal to the width of the staging area; therefore, an axial offset of 3 m is required for the layout examined. A typical forklift AGV is able to extend forks to pick up pallets 2m distant from the truck. The ccd camera can be mounted 1m on the farside of the pallet with respect to the AGV track to solve the "field of view" problem.

In order to reduce time for the positioning operation, the AGV is kept in motion at moderate speed and the deceleration of the AGV required to bring it to a stop in front of the target is calculated. There is a considerable difference in travel time when the AGV is permitted to decelerate from a moderate velocity and when it is moved at 'creep velocity' until it reaches the target. The extra time spent can prove much more expensive than a controller which governs the speed and displacement of the AGV. The velocity-distance plots, which were obtained by an application of the velocity-distance and time-distance equations, reveal the effect of initial velocity on deceleration. The relevant equations of motion are:

$$v_2^2 = v_1^2 + 2\, f\, \Delta s$$

where v_1 and v_2 are the initial and final velocities of the AGV, -f is the deceleration which

[3] Wide angle lens 17mm f4MD by Minolta corp. Angle of view=104 degrees

reduces the velocity over a distance 'Δs' to zero.

The deceleration may not exceed the product g μ, where g is the acceleration due to gravity and μ is the coefficient of friction between the track and the wheels of the AGV.

There is considerable latitude in the allowance for positioning the forks, as the clearance between the forks and the pallet opening[4] is 5 cm and the random error is ± 5mm. This is demonstrated by simulating the deceleration of the AGV under two forms of control: 1) Model following control and 2) Fuzzy logic control. The simulation was written in MATLAB, because of the ease of handling matrices in the package.

5.2.1.1 Model following control

The AGV deceleration required so that it comes to a stop when it reaches the target (the pallet) can be calculated if the initial velocity and the distance to be covered are known. The deceleration is found from the roots of the equation: $\Delta s = v_1 \Delta t + (1/2)\, f\, \Delta t^2$.

$$\Delta t = [-v_1 \pm \sqrt{\{v_1^2 - 2 f \Delta s\}}]\, /\, f$$

which is derived from the relation $\Delta s = v_1\, \Delta t + \frac{1}{2} f\, \Delta t^2$. The negative root of the quadratic is naturally rejected for positive values of Δs. When the deceleration is zero, time is calculated from the relation $\Delta s = v_1\, \Delta t$. V_2 and v_1 denote final and initial velocities, s is the distance to be covered, and f is the required acceleration. V_2 equals zero, and therefore f has a negative

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[4] BT Systems product profile for the F-30/40 Sideload Forklift. BT Systems Inc. 7000 Nineteen Mile road, Sterling Heights, MI 48078. 313/254-5200 Telex:235427

sign, denoting deceleration of the AGV. Assuming that 10 images are captured and processed every second, and there is a random error in determining the centroid distance of the target which is normally distributed with a mean of 0 and a standard deviation of 1 cm, [i.e. 68% of the data lie in the interval $\pm$ 1.0 cm]. the deceleration can be recalculated at every stage and the deceleration can be revised.

The assumed rate of capturing images (10/second) is reasonable since hardware implementation of image processing software is capable of accommodating 30 frame/second image capture and processing rates[5]. The controller is necessary since the exact location of the pallet is not known a-priori, and the vision signal provides the information needed to control the motion of the AGV. Reasonably accurate positioning is achieved by model following control (final location of the target<=0.5 cm). It is necessary to incorporate logic to prevent 'backtracking', i.e. at times the error in reading the distance to the target leads to the conclusion that the AGV has overshot the location it is supposed to occupy when the next image is captured. This is clearly not possible unless the AGV slips forward, therefore the deceleration is adjusted assuming that the AGV has overshot by half the distance to the location it is supposed to occupy when the next image is captured. The results of the simulation, which are presented in the next chapter, are compared with fuzzy control positioning.

5.2.1.2 Fuzzy control simulation

The simulation of position control using fuzzy logic can be broken down into the following steps:

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[4] Private communication with Diffracto Ltd., Windsor, Canada.

1. The input and output variables are grouped into trapezoidal fuzzy categories.
2. The input signal (from the ccd camera) is grouped into the appropriate fuzzy set and it's membership value (between 0 and 1.0) in that set is calculated.
3. Fuzzy rules are employed to generate a fuzzy output in response to the input.
4. Defuzzification of the fuzzy output is carried out by calculating the centroid of the polygon describing the fuzzy output.
5. The output is supplied as the input acceleration in a simulation model of AGV motion.

An error signal is fuzzified to a symmetrical trapezoidal distribution 2 units wide at the base and 1 unit wide at the top. The error signal is the difference of the actual and desired motor deceleration as the AGV moves towards its final destination at the staging area. Images are captured while the AGV is in motion, and normally distributed random error (standard deviation of 1 cm and zero mean) is added to the distance measurement to simulate random error in distance measurement. The deceleration is adjusted in response to the input signal. The desired motion of the AGV is modelled by using Newton's laws of motion. Model following control, where the acceleration is corrected to the new value at every iteration also brings the AGV to a stop at the final destination. The random error in measuring distance can be handled by using rule based fuzzy logic control where the deceleration error is the input to the fuzzy controller. The deceleration is corrected by adding the fuzzy controller output to the old acceleration.

One difference between the two forms of control is the model free operation of the fuzzy logic controller. An interesting feature is the possibility of backtracking. In the absence of control logic which limits the magnitude of the random error, it is sometimes possible that the controller thinks it has travelled backwards, and adjusts acceleration accordingly. Both model following control and fuzzy control bring the AGV to it's destination eventually, travelling backwards is definitely not desirable. Therefore, a criteria which sets the distance travelled to half the distance which would be travelled at the velocity during the previous time step, is included in the controller as in the case of model following control. The AGV is brought to a stop when it is within ±1 cm of the target. This is well within the 5 cm compliance provided by the pallet.

● **Explanation of fuzzy logic control:**

The input can be put in one of three categories: low, medium, or high. Thus if sensors read a lower than desired input, the output is increased in an effort to compensate. Likewise a high input calls for low output to rectify the error. The governing fuzzy rules are summarized as:

1. IF input is low THEN output is high.
2. IF input is medium THEN output is medium.
3. IF input is high THEN output is low.

The input and output memberships are trapezoidal fuzzy sets as shown in **Figure 5.7**. The implicit assumption here is that the expected inputs and the outputs will lie in the range -5..5, which are the scaled magnitudes of the maximum and minimum input, i.e. error, and output. The calculation of an output from a given input is carried out as shown:

Determine:

1. Input and output fuzzy set membership functions.
2. Membership function for input variable.
3. Relation matrices corresponding to various fuzzy rules.
4. Overall composition array calculated as a minimization operation over the composition array corresponding to every fuzzy rule.

The relation matrix R corresponding to a fuzzy rule IF A THEN B, where A and B are fuzzy sets, has to be determined for each set of rules. Subsequently, the composition array is calculated from the input and each relation matrix (Zadeh 1973). This operation is analogous to matrix multiplication, with the product and addition operations substituted by `maximum' and `minimum' operations. The supremum of the composition arrays corresponding to each fuzzy rule is the fuzzy output array. The centroid of the fuzzy output set provides a crisp value which is an input deceleration for the AGV motion model. The distance travelled is calculated using equations of motion for uniform deceleration.

In this example, it is assumed that both inputs and outputs comprise three membership functions categorised as 'low', 'medium' and 'high' ranging in value from -5 to 5. Fuzzy membership functions for both input and output variables are presented in **Figure 5.7.** The computation steps required to calculate the output corresponding to a fuzzy input are: (a) Generate membership function arrays. (b) Calculate relation matrices for every rule by applying minimization operator on the cross product of membership functions. The resulting matrices corresponding to rules 1, 2 and 3 (explained in the preceding paragraph) are presented in the form of 'mesh' plots in **Figure 5.8.** Determine composition arrays by applying max-min operator on the cross product of the input membership function and the relation matrices. The centroid of the output polygon provides a crisp value for the subsequent input deceleration to the AGV motion model. An excellent discussion of the computation steps is to be found in Zadeh (1973).

In conclusion, it is clear that two very important benefits of using vision based positioning are:

1. Reduction of time needed for moving pallets
2. Permitting autonomous AGV operation of the process of picking up pallets

These conclusions are substantiated subsequently by simulating the process {P} in SIMAN,[6] a simulation software.

Table 5.1 Regression results of ccd camera calibration data (Figure 5.5)

Regression parameters	Value
Standard error of "y" estimate	± 5.02 pixels
Each pixel (centre of the field of view)	0.22 mm
Error of reading position	1.1 mm
Correlation coefficient (r^2)	1.0
Number of observations	11
Slope (sensitivity)	8.7 pixel/cm
Y-intercept	-3.9

[6] Simulation software from 'Systems Modeling Corporation.'

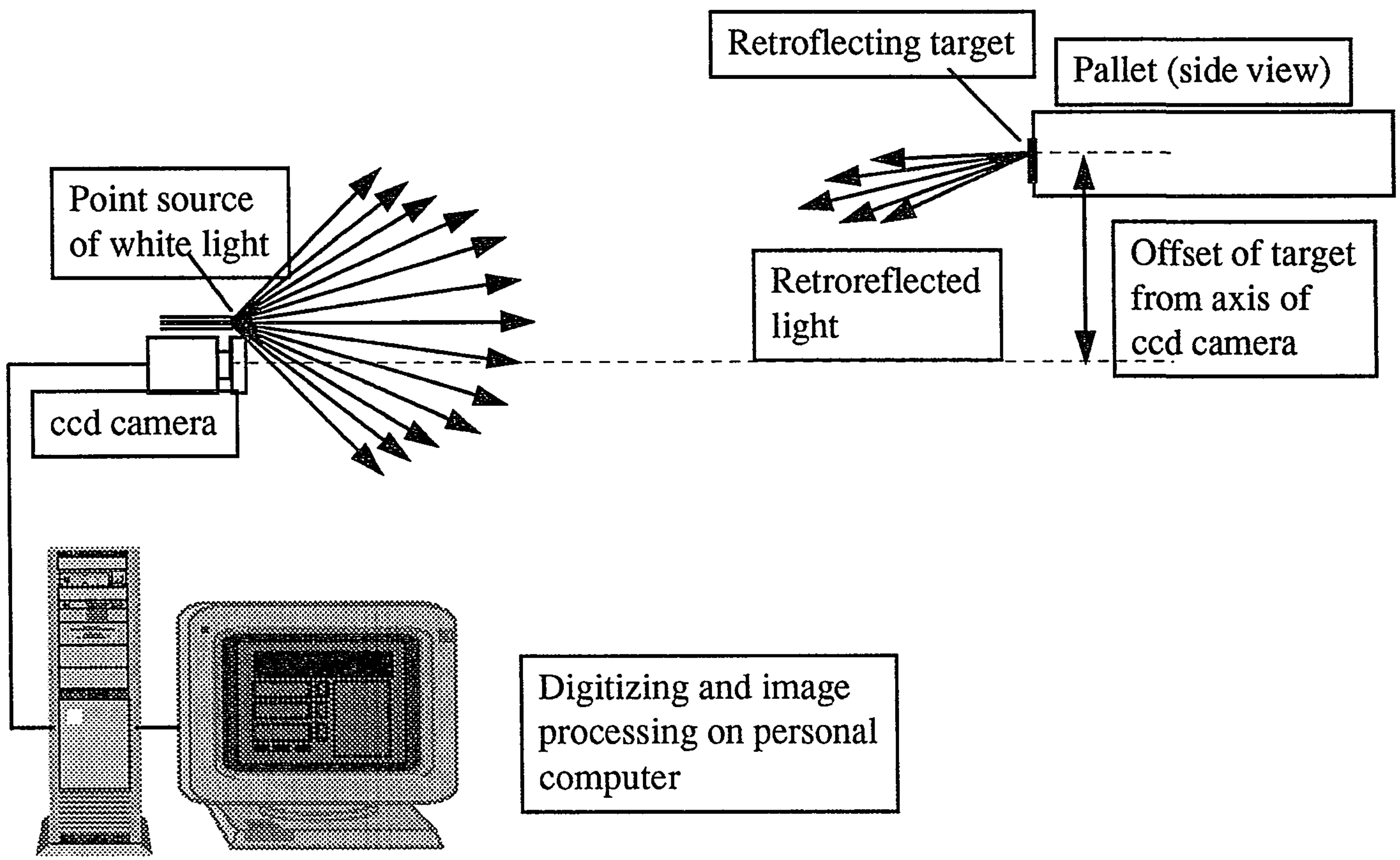

Figure 5.1 Retroreflecting target offset measured by a ccd camera

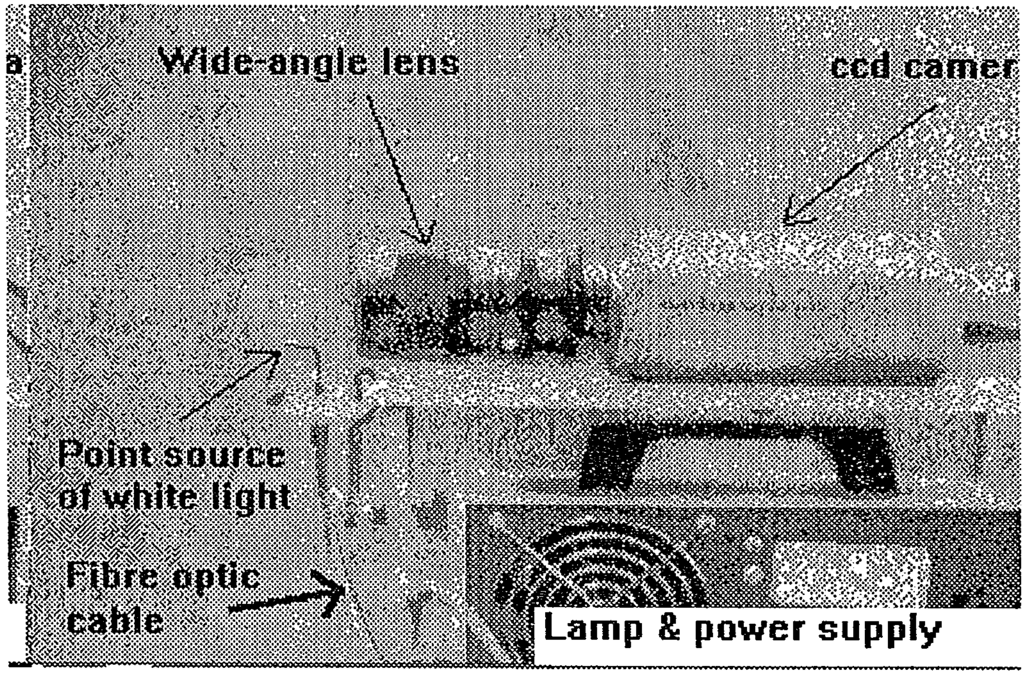

Figure 5.2 ccd camera set-up

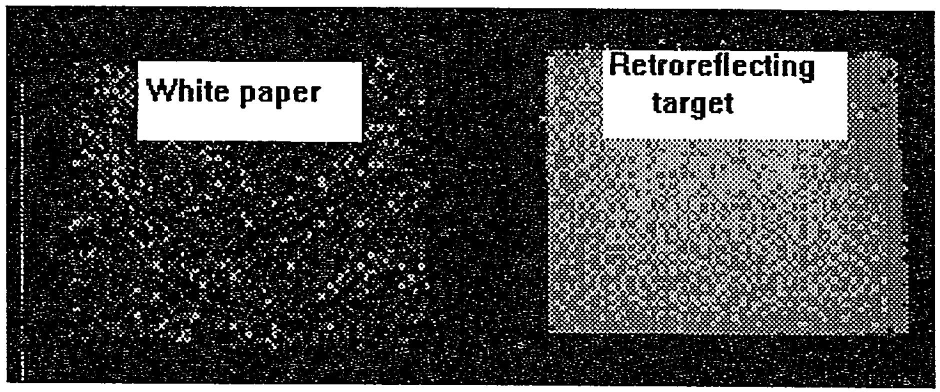

Figure 5.3 Comparison of images: retroreflector and white surface

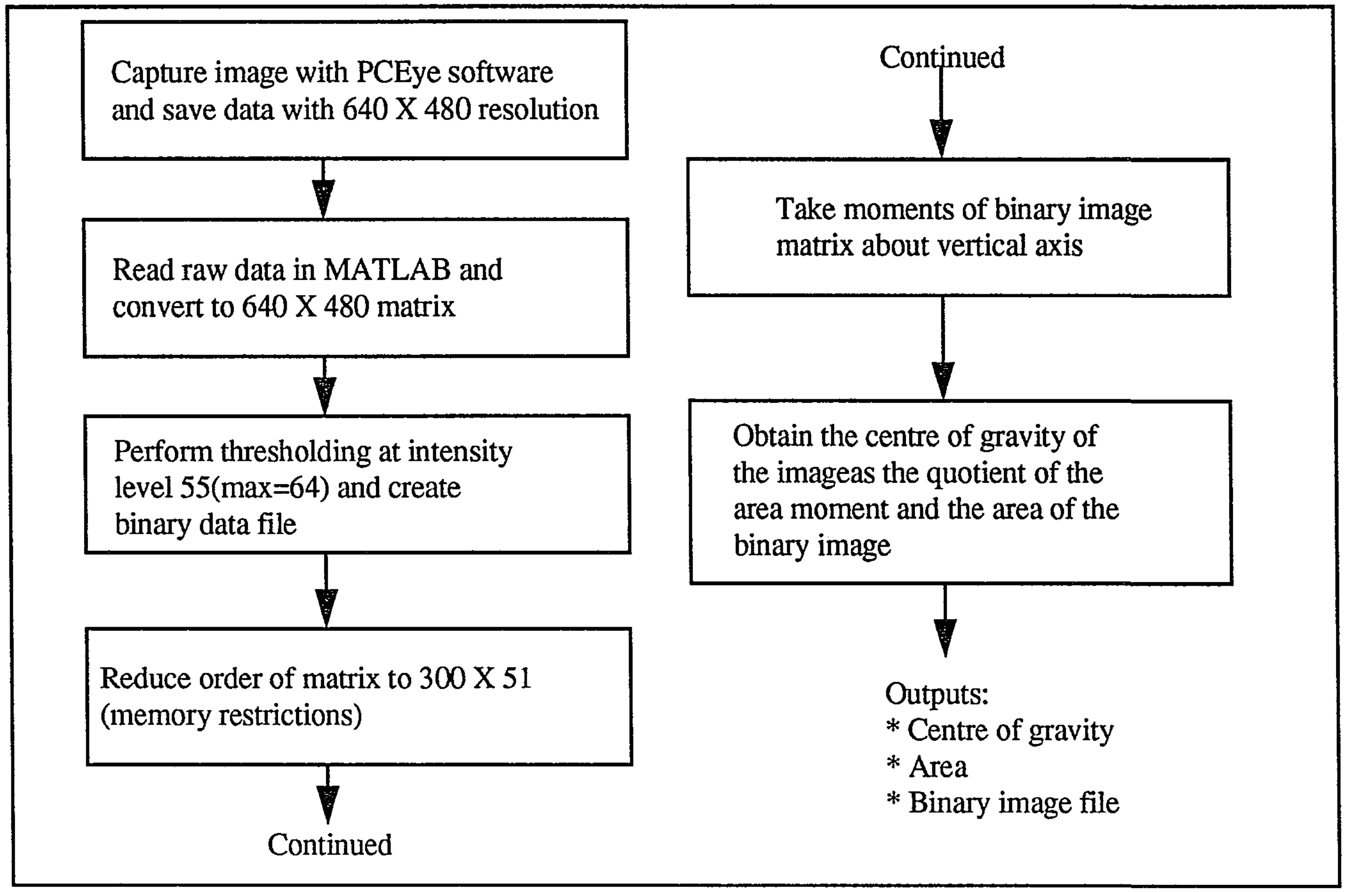

Figure 5.4 Flowchart of procedure for calculating target location

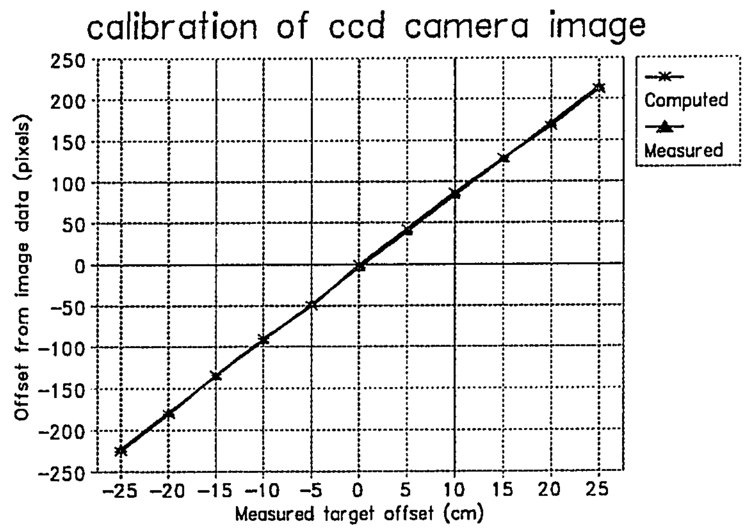

Figure 5.5 Comparison of camera determined target location with measured values

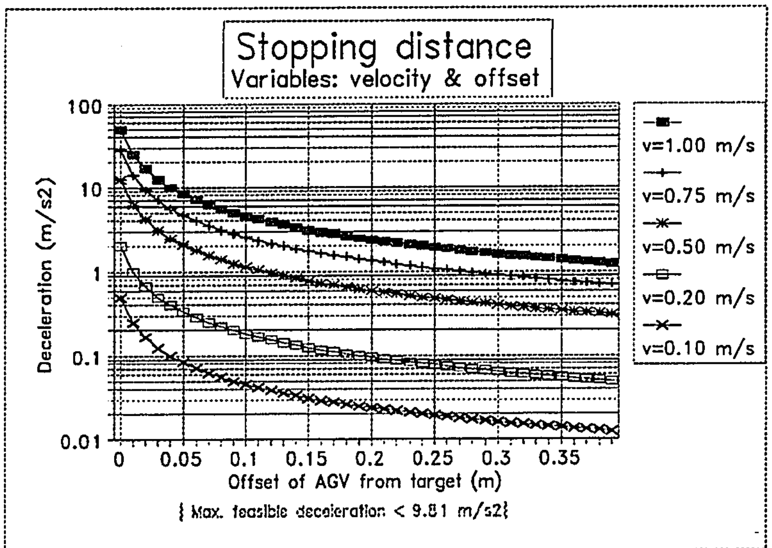

Figure 5.6 Deceleration required by AGV to slow to a stop

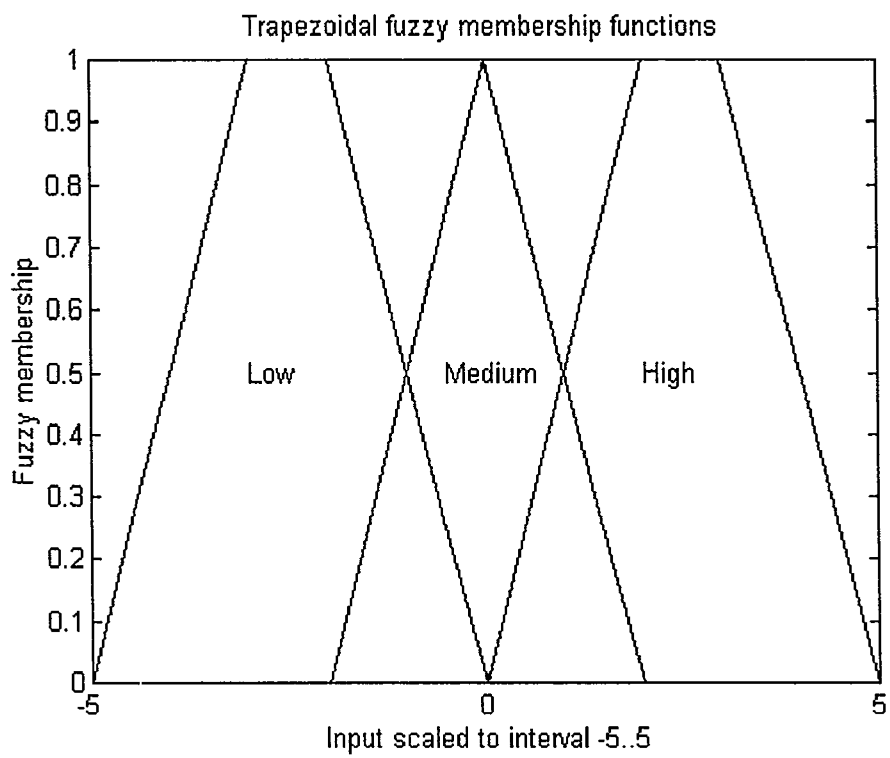

Figure 5.7 Trapezoidal fuzzy membership functions

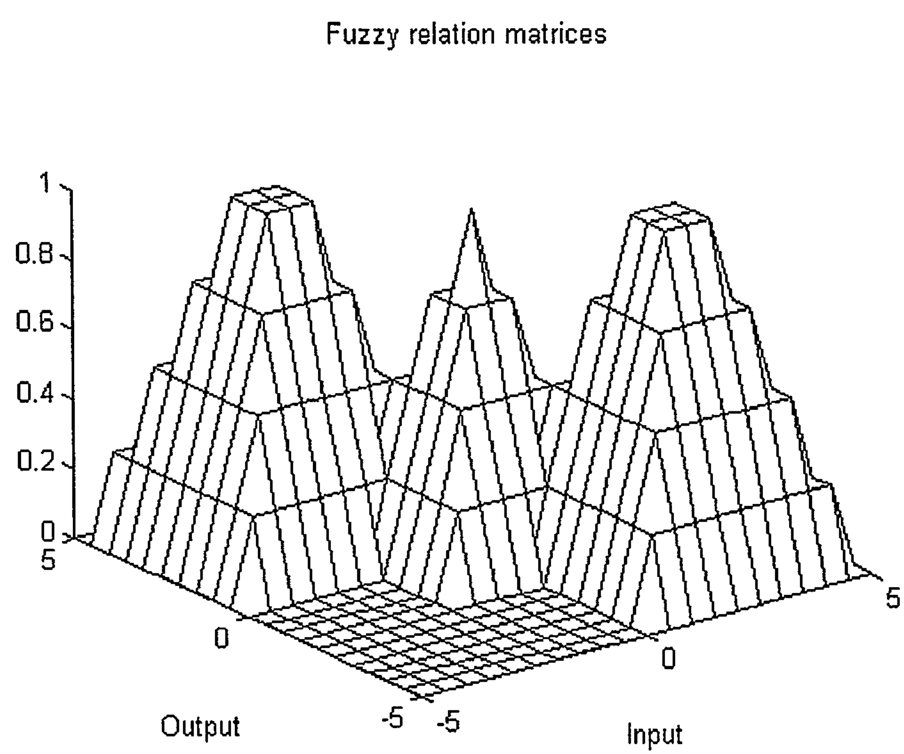

Figure 5.8 Fuzzy relation matrices

6.0 SIMULATING THE PROCESS [P] WITH SIMAN

The process [P] of carrying pallets from the staging area adjacent to unloading to a conveyor can be simulated conveniently in SIMAN, a simulation software (SIMulation and ANalysis software). Note that other simulation packages could also be used for the purpose, for example, "AUTOSIM" is a family of software products which can be used for creating animated simulation models of mechanisms and production processes, with automated statistical processing of information generated from the simulation. This would be an excellent choice for performing the type of modelling and simulation work described. For the purpose of demonstrating the merits of the modelling framework, however, SIMAN was found to be quite adequate. Statistical analysis was performed manually, and the output processor built into SIMAN did the data processing very rapidly. Given the discrete event model of the process (discussed in section 3.3), the process [P] can be described as a sequence of events.

6.1 Process description

The process can be described in the form of a logical flow of events, which are translated into SIMAN constructs:

1. Trucks arrive at the receiving docks with a mean interarrival.
2. "Pallets waiting" message is generated and passed on to the AGV.
3. If AGV is free;

   Free AGV moves to the unloading docks from its current location.

   Else if AGV is busy;

   Request is added to a queue, and pallet waits until AGV is free.
4. AGV travels to pallet following velocity profiles which depend on the path followed

and AGV acceleration, mass, wheelbase and height of the centre of gravity. The time of travel depends on the velocity profiles as discussed in chapter 4.

5. The AGV is positioned in front of the pallet. Positioning may be carried out by

   - Using vision sensors to read the distance of the AGV to the pallet location, and controlling the position adaptively or with Fuzzy logic;

   or

   - Moving at a creep velocity when the AGV is "close" to the target (a metal plate in the AGV track triggers the signal to slow to creep speed), and stopping when a limit switch is triggered.

6. The AGV picks up the pallet. The time taken for this event is obtained from the velocity at which the forks move up/down and in/out.
7. The pallets are moved from the unloading docks to the conveyor. The velocity is found as discussed in step 4.

These steps are repeated until all the pallets are moved from the unloading docks to the conveyor. A schematic representation of the process is presented in **Figure 6.1.**

The SIMAN model of the process is made up of a series of commands. Refer to Appendix * for a detailed explanation.

The interarrival time of trucks is assumed to be exponentially distributed with a mean ranging from 10 minutes to 30 minutes. Simulation results obtained by varying interarrival times provide information regarding the feasible operating region for a given set of conditions. The probability distribution chosen has the property of closely simulating true random arrival patterns, on account of the 'lack of memory' exhibited; that is to say, the probability of occurrence of a current event described by the exponential distribution has no effect on the probability of occurrence of subsequent events. The arriving trucks send a request message to the AGV controller. If the AGV is busy, this request is added to a queue. The schematic in **Figure 6.1** represents these events.

Every truck carries a number of pallets. From the given dimensions of a typical pallet, which is taken to be 825 mm by 1100 mm in size, a truck may conveniently carry 10 pallets stacked next to each other. Therefore, the batch size of every arriving entity is assumed to be 10. The pallets are assumed to be carried by a forklift AGV one 'stack' at a time. The restrictions to stack size is the total weight of one stack, which is assumed to be in the region of the maximum payload, i.e. 1364 Kg.

The loading/unloading time is a function of the speed with which the forklift can safely raise and lower a pallet at the staging location and at the conveyor, which is the final destination of the pallets. This time is 2 seconds, and is modelled as a delay at the particular location of the pallet loading/unloading event. Like the previous two inputs, this is a part of the model file in SIMAN.

Typical velocities of commercial forklift AGVs range from 0.10 m/s to 1 m/s. These are obviously 'safe' velocities, and can be significantly increased to reduce time taken to carry out the process. AGV velocities considered in the simulation are in the range of ≈3.5 m/s .. 0.8 m/s. The numbers are arrived at from a consideration of

- Torque limited velocities for a 15 kW AGV (power output at a velocity of 4m/s)
- Commercial AGV velocity (maximum drive speed in automatic mode) of 1 m/s
- Adaptive control positioning
- Fuzzy control positioning and
- Creep feed positioning (limit switch trigger)

The velocities are determined by accounting for the time taken to travel the various links of the AGV guidepath, assuming that the minimum velocity while negotiating a curved link is the friction and toppling limited velocity of the AGV, which equals 2.79 m/s for the shorter (length of curved path = 4m) curves and 3.13 m/s for the longer (length of curved path = 5m) curves. These are determined using the MATLAB code used to generate **Figure 4.2,** assuming μ=0.8 and h=1.5m.

The velocity at the beginning and end of various links, and the average velocity index(AVI), equal to the quotient of the overall distance and time, are presented in tables 8.1 and 8.2. The velocities while going around a curve and while positioning are much smaller as compared to the velocity while travelling along straight links, and have to be taken into account in the simulation. A comparison of the flowtime for torque limited acceleration and fuzzy position control is made with the current situation with most AGV material handling applications, where a moderate velocity of 1 m/s is used in conjunction with a positioning speed of 0.1 m/s. The velocity of positioning with fuzzy control comes out to 1.35 m/s. These modifications are necessary since it is difficult to account for the effect of acceleration on the travel time in SIMAN, by using the value of acceleration and the initial and final velocities only.

The description of the model conforms to the simulator model[1], that is to say, events occupy known time segments (as an example, in the SIMAN model discussed, the movement of the AGVs along various links in the network are calculated from velocity and acceleration / deceleration, etc. so that an atomic event consisting of moving from one end of a link to another occupies a definite time segment) and follow a sequence of states which is dependent on input received (implemented in the concept of 'visitation sequences' and IF - THEN rules governing the movement of transporters in SIMAN).

6.2 Assumptions

In modelling and simulating the process, a large number of simplifying assumptions have been

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[1] Discussed in section 3.1

made.

1. The model focuses on the process of carrying goods in the form of pallet loads from staging to the conveyor. The remaining portion of the distribution centre is assumed to have negligible effect on the process under study. This implies that: (i) The pallets supplied to the conveyor are promptly carried off to it's destination with zero delay and (ii) In case of 'traffic jams' the pallet loads are diverted to an 'infinite' sink, which is a temporary storage area with infinite capacity.
2. Communication between AGV's, sensors, and process controllers [assuming hierarchical control structure, where the process controller oversees all the events in the process under study], and decision making by the controllers, are instantaneous.
3. The problem of obstacle avoidance is not considered in the model, and it is assumed that unexpected obstacles on the path of the AGV are not encountered.
4. The floor (surface on which the AGVs move) is assumed to be quite flat and devoid of unevenness which may affect AGV speed or tendency to topple.
5. The coefficient of friction between the wheels of the AGV and the floor is assumed to be constant over the entire track, and not a function of location or time.
6. Pallets are assumed to have near perfect geometry and high integrity; i.e. they are not susceptible to breakage or deformation under normal transporting conditions.
7. Off centre AGV loading is not considered. This assumption can be justified on the basis that the weight of the AGV is greater than that of the pallet, and the suspension ensures that the load does not cause the AGV to slew while accelerating.

6.3 Variables considered while simulating the process

1. Coefficient of friction between AGV wheels and floor

The friction puts a limit on the maximum velocity while going around turns. The torque considered is not sufficient to bring moderate values of friction (>0.5) into play when accelerating along straight links in the AGV network.

2. Mass of AGV

The acceleration of the AGV and the tendency to topple are influenced by its mass. The value used is 3997 Kg, which includes the payload.

4. Maximum permissible AGV velocity

10 m/s (36 Km/hr) is the limiting AGV velocity. This value is never approached. From the velocity graphs presented in the "results", it was noticed that the AGV never exceeds a velocity of 5.8 m/s (when following the power limited velocity profile on link 3).

5. Power available

The AGV was assumed to be powered by a motor generating 15 kW at an AGV velocity of 4 m/s. The corresponding maximum acceleration equals 0.94 m/s^2.

6. Centre of gravity and wheelbase of AGV

Toppling tendency is directly related to these dimensions. From **Figure 4.2,** it is seen that the AGV starts to topple when the friction coefficient goes above 0.6. Lowering the centre of gravity and increasing the wheelbase would improve stability. However, this may not always be practicable.

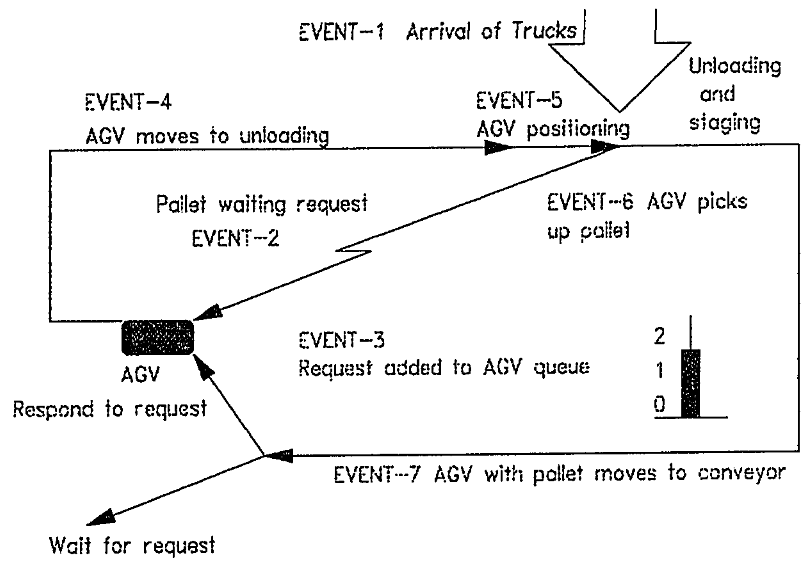

Figure 6.1 Schematic representation of the process model

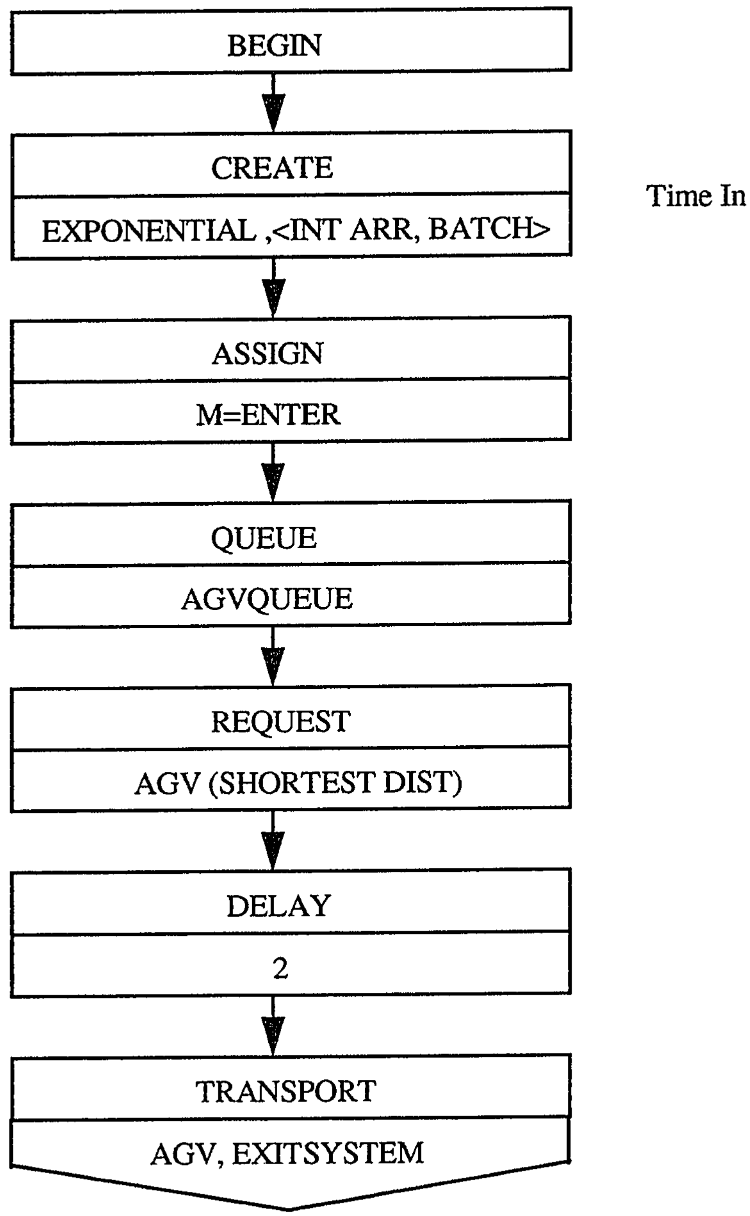

Figure 6.2a Siman model flowchart

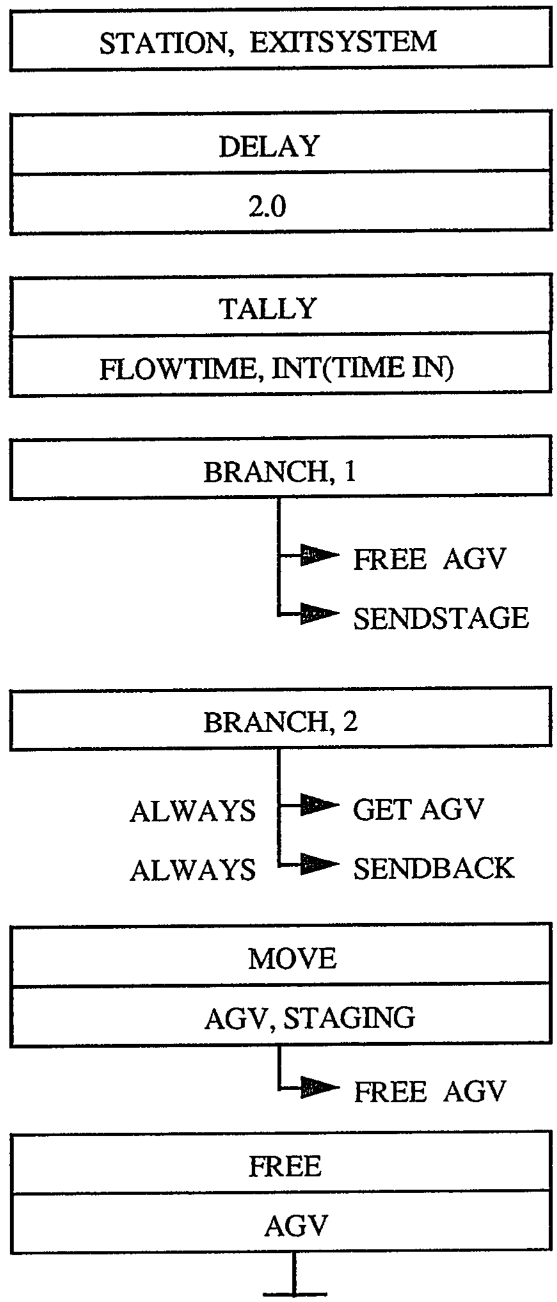

Figure 6.2b Siman model flowchart

7.0 RESULTS

In the simulation model of the process of carrying pallet loads from the staging area next to the unloading docks in a distribution centre, the number of pallets waiting was the variable of interest. A rapid increase in the number of pallets waiting to be serviced by an AGV will indicate an infeasible situation.

Trucks carrying pallet loads arrive at the receiving dock. Apart from the interarrival time, two factors which influence the process are:

- The time for positioning and
- The AGV velocity profile;

These determine the average velocity of the AGV. The average velocity index (AVI) is the number used in place of AGV velocity while modelling the process {P} in SIMAN. The relevant calculations are presented in **Tables 7.1** and **7.2**, where the average AGV velocity while accelerating and decelerating across a link is calculated for an unloaded AGV, and the overall time required to go across all the links is found. The AVI is determined as the quotient of the total distance and time.

The effect of AGV velocity profiles significantly affects system performance in the process modelled because of the following reasons:

1. The staging area has to be cleared of all pallet loads in the shortest possible time. This involves rapid, repetitive motion of the AGV from the staging area to the conveyor.

2. The AGV is required to accelerate during linear motion and decelerate every time it approaches a curved path.

The benefits of rapid automated positioning is obvious, since a reduction in the average positioning time for every pallet load makes it easier to justify the replacement of human operators for this type of repetitive task. The effect of controlled positioning as opposed to 'creep feed positioning' with proximity sensors, currently the practice in automated goods distribution, is to drastically reduce the time needed for positioning the forklift.

7.1 Velocity profiles

Graphs of AGV velocity profiles for the various links in the AGV flowpath as described earlier in **Figure 3.2**, and the variation of time, are calculated and presented in **Figures 7.1 to 7.11**. When the maximum velocity is not permitted to exceed 1 m/s, the flat profiles predict little effect of increased acceleration on time of travel. This is not so when we permit torque and friction limited maximum velocities, and a large reduction in time is achieved. The friction and toppling limited velocity is found from **Figure 4.2,** where a velocity surface provides the feasible maximum velocities corresponding to various curve radii and friction coefficients. Half circle perimeters of 4m and 5m are the lengths of short and long curved links respectively, and a coefficient of friction of 0.8 was assumed in order to obtain the toppling and friction limited velocity of the AGV. This value turns out to be 2.79 m/s for the short links (R=1.31m) and 3.13 m/s for the long links (R=1.59m).

The velocity profiles presented in **Figure 7.1** are for link "1a." Link 1 is divided into two equal parts, each of length 2 m. The average distance to a waiting pallet is assumed to be 2 m from one end of link 1, and the AGV is required to slow down from the friction and toppling limited velocity at which it travels as it approaches link 1, to a stop. This half of link 1 is link "1a," and the time required for positioning is obtained by simulating controlled deceleration with MATLAB. These results are provided in the next section. After picking up the pallet load, the AGV accelerates from zero velocity along link 1b and attempts to reach the velocity at which it is permitted to enter the next link (link 2). The velocity profiles while the AGV travels along its path are presented in **Figures 7.1 to 7.11**.

7.2 Vision based positioning

The coordinates of the target (retroreflecting) are utilized to determine the distance of the target from the AGV. It is assumed that ten readings are obtained every second, and processed to generate AGV acceleration. The control is simulated with MATLAB to investigate how well a controller will respond to visual data which has a normally distributed error (in measuring distance). These results as derived from the simulation of fuzzy control and adaptive control while positioning the AGV (vide chapter 5) are presented in **Figures 7.12** and **7.13**. The displacement graphs in these figures exhibit the typical wavy displacement curve which is expected when random error is present in the displacement measurements. The error signal considered in the simulation is normally distributed with zero mean and a standard deviation of 1 cm. A detailed discussion of the process of using the visual data for control is included in chapter 5.

Clearly, currently the task requires more than one AGV. The same AGV, however is capable of performing the task if higher velocities are permitted on both straight and curved links, guarding against toppling while going around curves, and controlled, high speed positioning is incorporated while locating and picking up pallets. The savings are significant. In an automated environment, the absence of personnel in the staging area makes the comparatively higher velocities feasible. It may be noted that fuzzy controlled positioning movement is capable of providing stable control even when unknown nonlinearities exist in the model describing AGV movement. This result is in agreement with the paper by Wang (1993). It is also faster in some situations (in contrast to model following adaptive control), as has been demonstrated by the simulation results presented in **Figure 7.12,** although the adaptive controller can be adjusted to make it faster. The controller described in the dissertation is judged to be adequate for the given situation, as observed from the displacement curve presented in **Figure 7.13.**

7.3 Simulation output

On examining the SIMAN simulation output for the process [P], presented in **Figures 7.14 to 7.23**, the results for the transient state (duration of data collection=10^5s) and the steady state (duration=10^6s) shows little variation for all cases except those where the interarrival time drops below 15 minutes. These results focus on the higher AGV velocities obtained with zero load. The AVI of the loaded AGV with creep feed positioning control has the lowest value. Since the process starts to break down for the unloaded AVI values of 0.84 m/s, as observed from **Figure 7.23,** even when the interarrival time is the maximum value of 30 minutes, still lower AVI values (as with a loaded AGV) are not used in the simulation runs.

The transient state simulation results, presented in **Figures 7.14 to 7.18**, indicate the queue does not become large (>2) when the AVI is 2.11 m/s and higher. In **Figure 7.14**, the interarrival time is 10 minutes, and the process is in control when the AVI is 2.11 m/s or greater. When the interarrival time increases to 15 minutes, as seen in **Figure 7.15,** an AVI of 2.11 or greater causes queue lengths less of than 1. However, for an interarrival time of 30 minutes, the queue is less than 1 even when the AVI is 0.84 m/s.

The steady state output data from **Figures 7.19 to 7.23**, like the transient state simulation results presented in **Figures 7.14 to 7.18,** indicate the presence of a clearly defined region of infeasibility. It is also seen that the transient behaviour of the process [P] does not conflict with the conclusions drawn from the steady state results, when transient behaviour and steady state results are compared through **Figures 7.14 to 7.23**. Unidirectional links and one AGV are considered in the simulation, so there is no conflict resolution or traffic control involved in this case. A moderate velocity of 1 m/s is taken as the velocity of a commercial AGV[1] with creep feed positioning at 0.01 m/s. When the interarrival time decreases to 10 or 15 minutes, the system starts to break down, and a drastic increase in the number of pallets waiting is observed. **Figures 7.14 to 7.23** present the results of the simulation runs. Five interarrival times were considered for an unloaded AGV and a combination of positioning control and AGV maximum velocity produced 5 distinct velocities, so a total of 25 cases are considered for the unloaded AGV. For convenience of caparison, the 5 velocity indices corresponding to each interarrival time are plotted on one graph. For example, in **Figure 7.14,** the queue length increases steeply with time when the average velocity index (AVI) is 1.00 m/s and 0.84 m/s. For higher values of AVI, i.e. 2.11 m/s, 3.41 m/s and 3.43 m/s, the queue length stays below 2. As expected, the number of waiting pallets increases as the velocity drops, but it is only a problem when the currently used values for AGV motion (velocities for a commercial AGV) are considered. The enhanced velocities possible with torque limited velocity profiles are able to handle the smaller interarrival times.

When the arrival rate is high, the material handling task requires more than one AGV. The same AGV, however, is capable of performing the task if higher velocities are permitted on both straight and curved links, guarding against toppling while going around curves and controlled, high speed positioning is incorporated while locating and picking up pallets. The savings are significant. In an automated environment, the absence of personnel in the staging area makes the comparatively higher veocities feasible.

7.4 Extension of simulation results

In the next section, the behaviour of the system comprising of unloading docks and AGV

[1] For details, see Table A-1 in the appendix.

pallet transport equipment is examined. Simulation results have indicated that the transient zone of operation does not pose a problem since the system does not show signs of going out of control, as would be suggested by sharply increasing queue lengths. The steady state results can therefore be used to study system performance not only for the simplified network discussed, but also larger networks where certain assumptions are met. Since we are concerned with steady state results, queueing theory analysis can provide some insight into the behaviour of larger systems.

7.5 Queueing theory analysis

This section deals with the investigation of steady-state behaviour of a distribution centre comprising 3 unloading docks and 3 AGVs. The objective is to extend the simulation result for a simple network using a "building block" approach to larger networks with multiple AGVs.

For the single loop network, AGV service time, μ, is deterministic, and $\mu<\lambda$, the expected value of the exponential interarrival rate. When there is one AGV and one unloading dock, the steady state probability of various states (defined by # of trucks waiting) and the queue lengths, are calculated using a Markov (birth-death) model. This is done by equating transitions to and from various states, as described in any text on queueing theory.

7.5.1 Markov models of M/D/1 queues

The steady state probability of 0 waiting is given by

$P_0=1-\rho$, where $\rho=\lambda/\mu$

where λ is the expected value of the exponentially distributed interarrival time of trucks carrying pallet loads, and μ is the deterministic service rate.

The queue length is given by:

$$L_q=\rho^2/2(1-\rho)$$

The result can also be applied to the case where a multiple number of AGVs carry pallets from one dock at a time. This situation is considered in the following section.

7.6 Overall description of the modified network

The network considered is depicted in Figure 7.24. Trucks carrying 10 pallets each arrive at dock#1. Trucks are diverted to docks 2 and 3 only when a queue develops at dock 1. Thus, the probability of trucks going to dock 2 and 3 only when a queue develops at dock 1. Thus, the probability of trucks going to dock 2 is the same as the probability of non-zero queue at dock 1, and the probability of trucks being diverted to dock 3 is equal to the probability of non-zero queues at dock 2 AND at dock 1. The trucks arrive according to a Poisson distribution at dock 1, and subsequently are redistributed according to the "overflow mechanism" described. The advantange of a greater number of docks is that trucks do not have to wait in queue to be unloaded. The pallets are unloaded at a free dock, and the truck is released. Pallets are picked up from the docks on a FCFS (First Come First Serve) basis. The rate at which trucks arrive at docks 2 and 3 are:

$$\lambda_{dock\,2}=\lambda P_0=\lambda\{1-\rho_{dock\,2}\}$$
$$\lambda_{dock\,3}=\lambda_{dock\,2}P_0=\lambda_{dock\,2}\{1-\rho_{dock\,3}\}$$

where ρ for docks 2 and 3 are:

$\rho_{dock\,2}=\rho_{dock\,1}\{1-\lambda_{dock\,1}/\mu_{dock\,2}\}$ and

$\rho_{dock\,3}=\rho_{dock\,2}\{1-\lambda_{dock\,2}/\mu_{dock\,3}\}$

The values of μ for docks 1,2 and 3 are calculated from a consideration of the AGV velocity which satisfies the dynamic constrains to motion, the time lost due to interference and the time needed for controlled positioning of forks at the loading docks.

7.7 Assumptions of vehicle motion

The AGVs travelling along the path (**Figure 7.24**) are assumed to travel at a constant friction or toppling limited velocity around the curved paths (the friction coefficient is assumed to be 0.8 as before); and it is also assumed that the AGVs always encounter a "conflict" situation whenever possible, i.e. when the last load from one dock and the first load from the subsequent dock interfere while moving down the AGV guidepath. This time loss is accounted for as an addition to the time required to service a truck. The time is calculated by making the assumption that the slower vehicle stops, and lets the faster one pass. The "zone" considered is 14.5 m and 13.1 m in length respectively for interference at docks 2 and 3. The velocity profile, and corresponding travel time are calculated for each "conflict" situation, and the time elapsed is added to the AGV service time.

7.7.1 Service time calculation

The lengths of various links traversed by the AGV is different when it travels to each of dock numbers 1,2 and 3. Since the motion is constrained by dynamic factors, a longer link permits acceleration for a longer time duration. When servicing dock #1, the AGV moves along an 8 m path prior to entering the loading link adjacent to the loading dock. When the AGV travels to dock #2 the velocities are slightly lower. The m-file which generates the time needed to unload a truck from dock #1 is presented in Appendix A (tryA.m). Similar files were written for docks 2 and 3 and the service times were found from the velocity profile graphs generated by the m-files. The trucks were assumed to arrive at the rate of 6 / hr. The service times at the three docks (with one AGV powered by a 375 N.m torque electric motor) turn out to be:

T_1=40.68 s T_2=41.06 s T_3=40.95 s

These numbers are arrived at by adding the time taken to traverse the network when the AGV goes to each of the docks 1,2 and 3, and represents the time needed by one AGV to carry one pallet from the dock to the conveyor and return to the staging link, or, alternatively, move to a dock in preparation for the next truckload of pallets.

Allowance for loading/unloading of 6 s each was made, and the time taken to travel the last link was subtracted from the total time of travel for 10 pallets, assuming that the last AGV travels to the staging station prior to going out to service the next truck load. The arrival rate was assumed to be 6 trucks / hr.

7.8 Results of the queueing model

As in most processes with random inputs, the system will go through a transient region, where the queue lengths at the various docks will exhibit variation with time during a simulation run. Simulation reveals that the process settles down to a "steady state" after a time interval of about 10^5 seconds. The probability of non-zero queue lengths at dock 1, and happens according to an "overflow mechanism." Therefore, once the steady state is reached at one dock, the probabilities at the other docks reach a steady state as long as the chance of

0 waiting is the maximum in dock #1 (so that overflow in one direction only occurs). Since dock #1 is cleared before waiting trucks at other docks are serviced, the movement of AGVs is similar to having one dock. Furthermore, since the AGVs need a greater length of time to travel around the path and unload a pallet as compared to the time taken at the unloading docks, the effect of increasing the number of AGVs is simply to decrease the service time {subject to the assumption about the possibility of lost time due to interference}.

The M/D/1 queueing model used to model the enlarged network makes use of the following assumptions:

- Markov process inputs (arrival rate according to a Poisson distribution)
- The service time is assumed to be deterministic.

The assumptions made regarding interference and length travelled seem to be justified on the basis that they provide "safe" (low) values of service rates, and a change in the assumptions regarding interference have very marginal effects on the total travel time. The results of probability of zero waiting and expected queue length corresponding to the situation matrix in Table 7.1 are tabulated in Table 7.2. These results lead to the conclusion that steady state behaviour of certain networks where the assumptions discussed are valid can be examined by making use of queueing theory. Thus, system behaviour can be rapidly predicted and modified by controlling the motion of the AGVs in the network. The queues which develop at the various docks when 1,2 and 3 AGVs are present are depicted in **Figure 7.24**. The extremely low queue lengths at dock 3 are close to zero. The queueing model results, and their relation to the results of the simulation model are discussed in chapter 8.

VELOCITY PROFILES ALONG AGV PATH

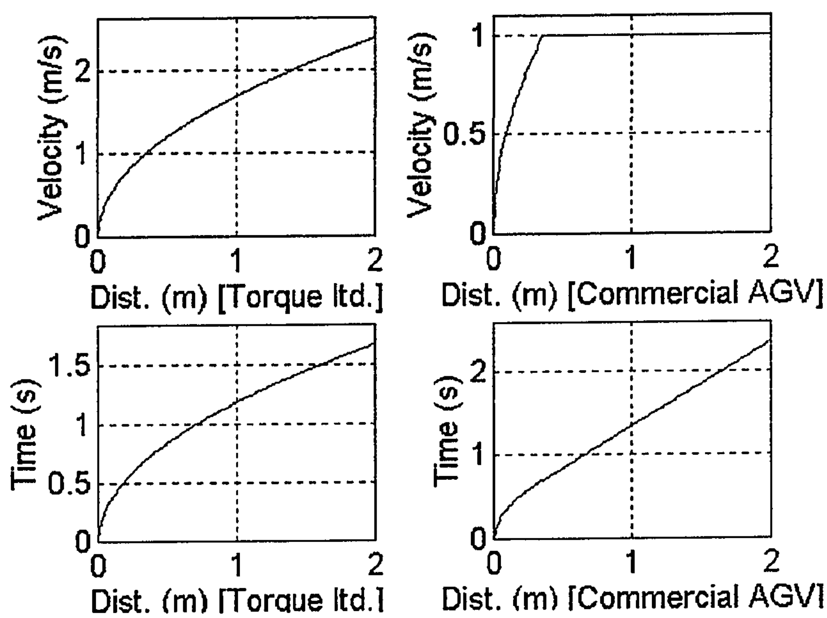

Figure 7.1 AGV Velocity profiles along link 1b for (1) torque limited velocity and (2) commercial AGV.

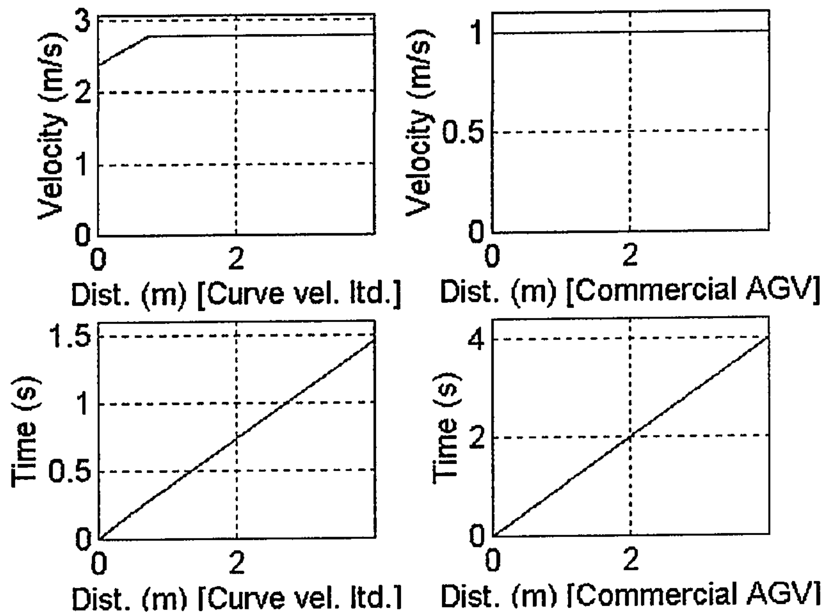

Figure 7.2 AGV Velocity profile along link 2 for (1) friction and toppling limited velocity and (2) commercial AGV going around a curve.

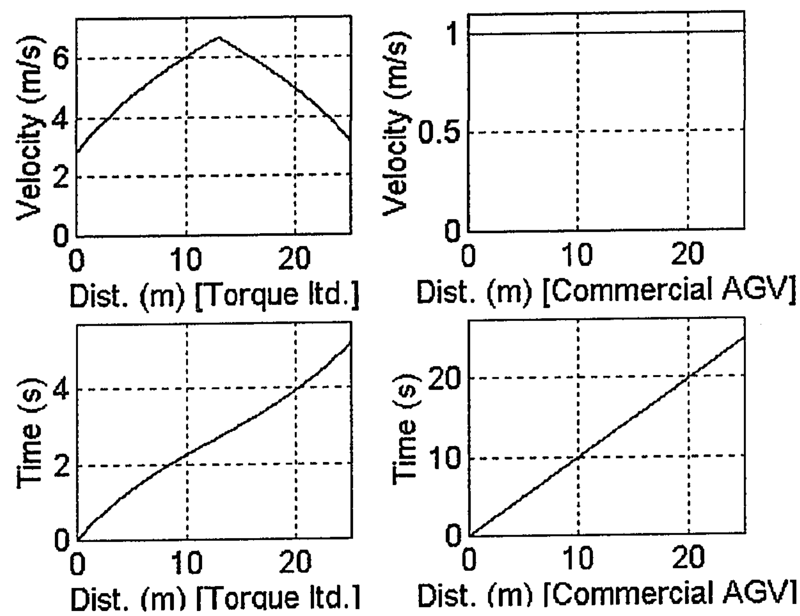

Figure 7.3 AGV Velocity profiles along link 3 for (1) torque limited velocity and (2) commercial AGV.

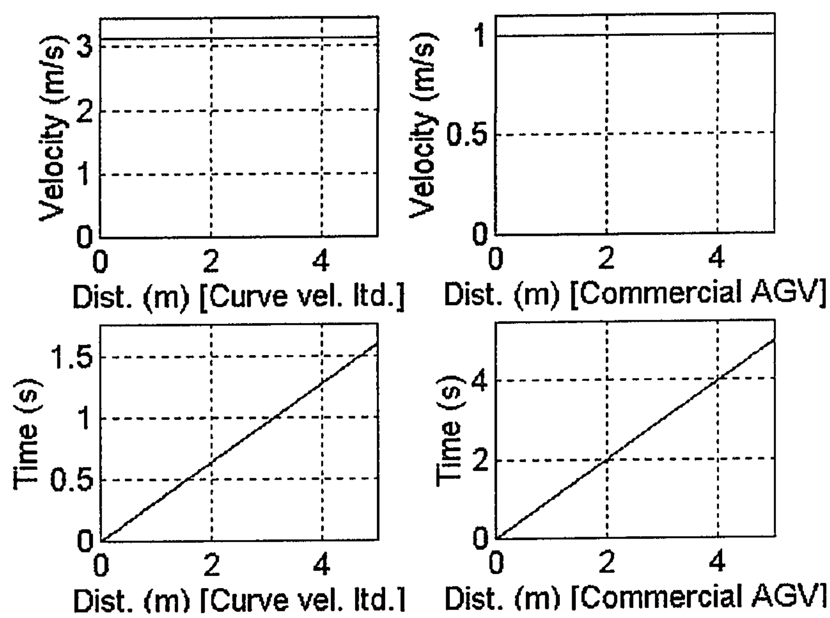

Figure 7.4 AGV Velocity profiles along link 4 for (1) friction and toppling limited velocity and (2) commercial AGV moving around a curve.

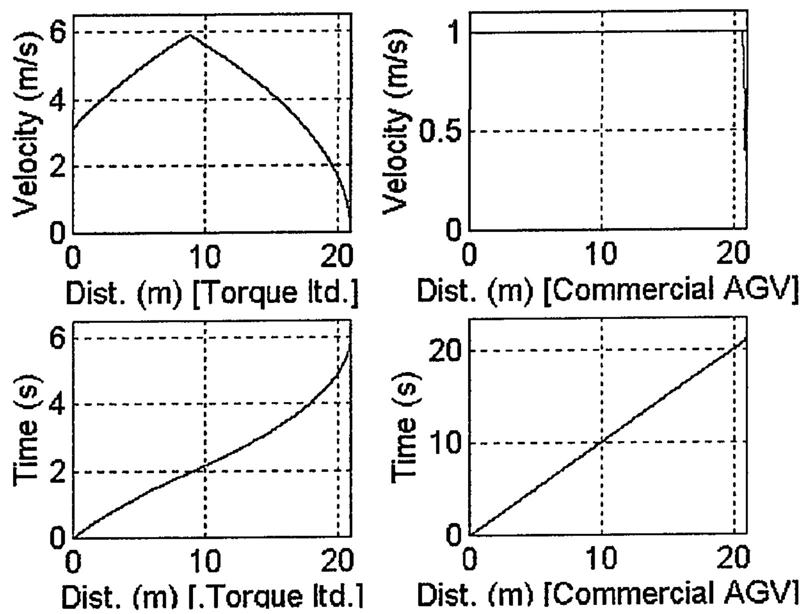

Figure 7.5 AGV Velocity profiles along link 5 for (1) torque limited velocity and (2) commercial AGV.

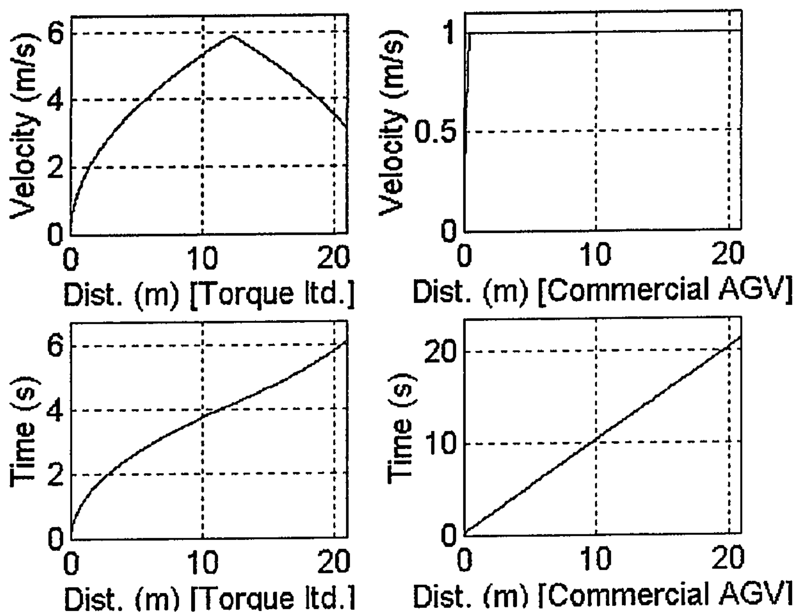

Figure 7.6 AGV Velocity profiles along link 6 for (1) friction and toppling limited velocity and (2) commercial AGV moving around a curve.

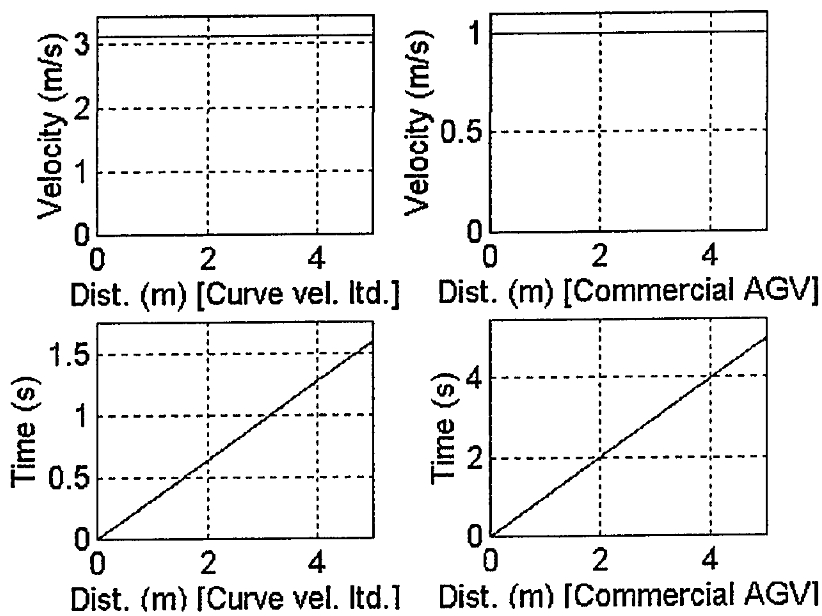

Figure 7.7 AGV Velocity profiles along link 7 for (1) torque limited velocity and (2) commercial AGV.

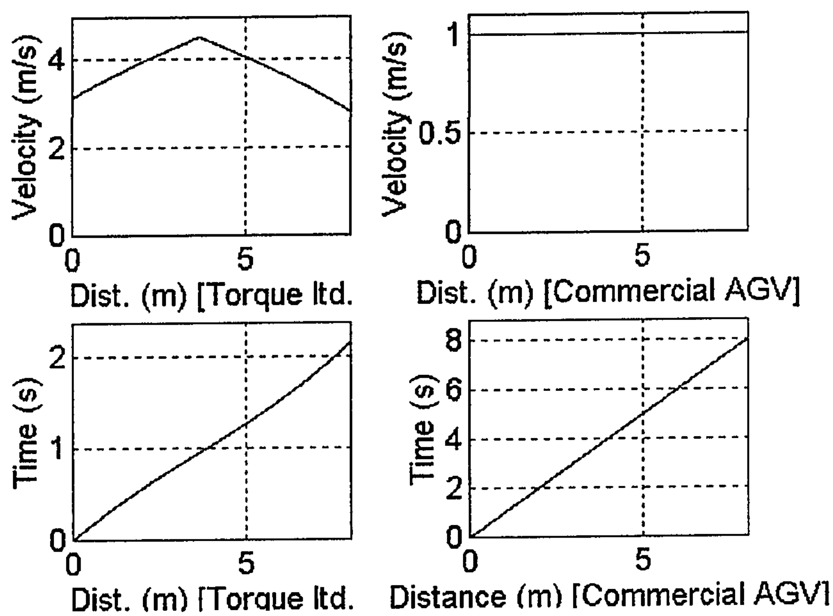

Figure 7.8 AGV Velocity profiles along link 8 for (1) torque limited velocity and (2) commercial AGV.

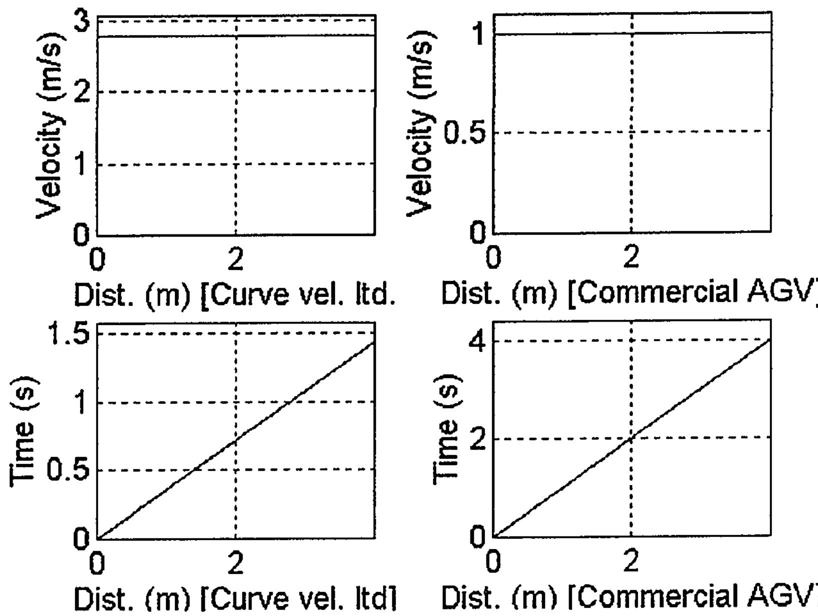

Figure 7.9 AGV Velocity profiles along link 9 for (1) friction and toppling limited velocity and (2) commercial AGV moving around a curve.

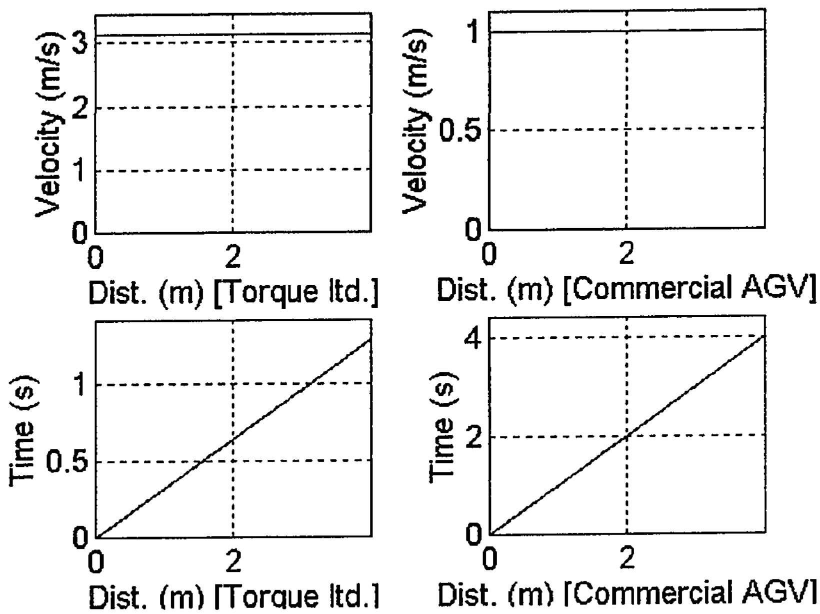

Figure 7.10 AGV Velocity profiles along link 10 for (1) friction and toppling limited velocity and (2) commercial AGV moving around a curve.

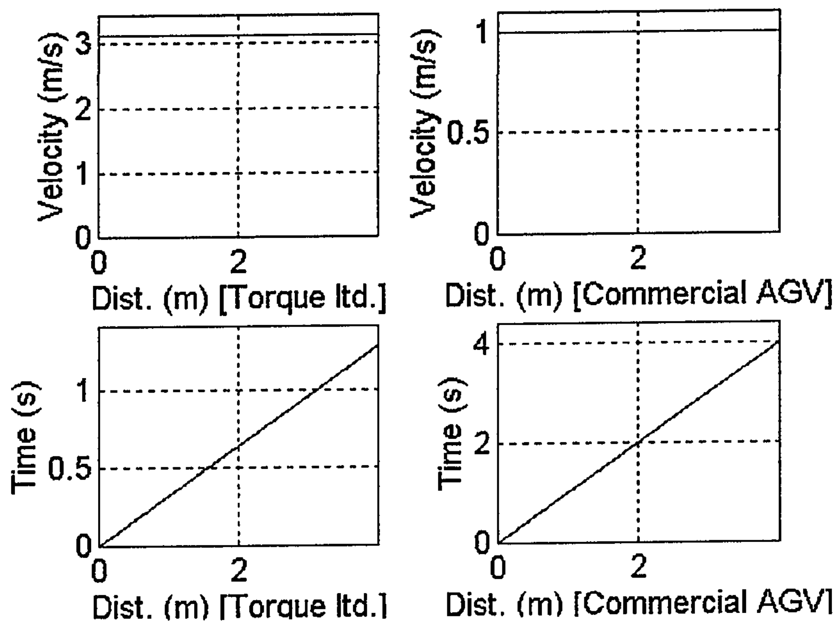

Figure 7.11 AGV Velocity profiles along link 11 for (1) friction and toppling limited velocity and (2) commercial AGV moving around a curve.

VISION-BASED POSITIONING CONTROL

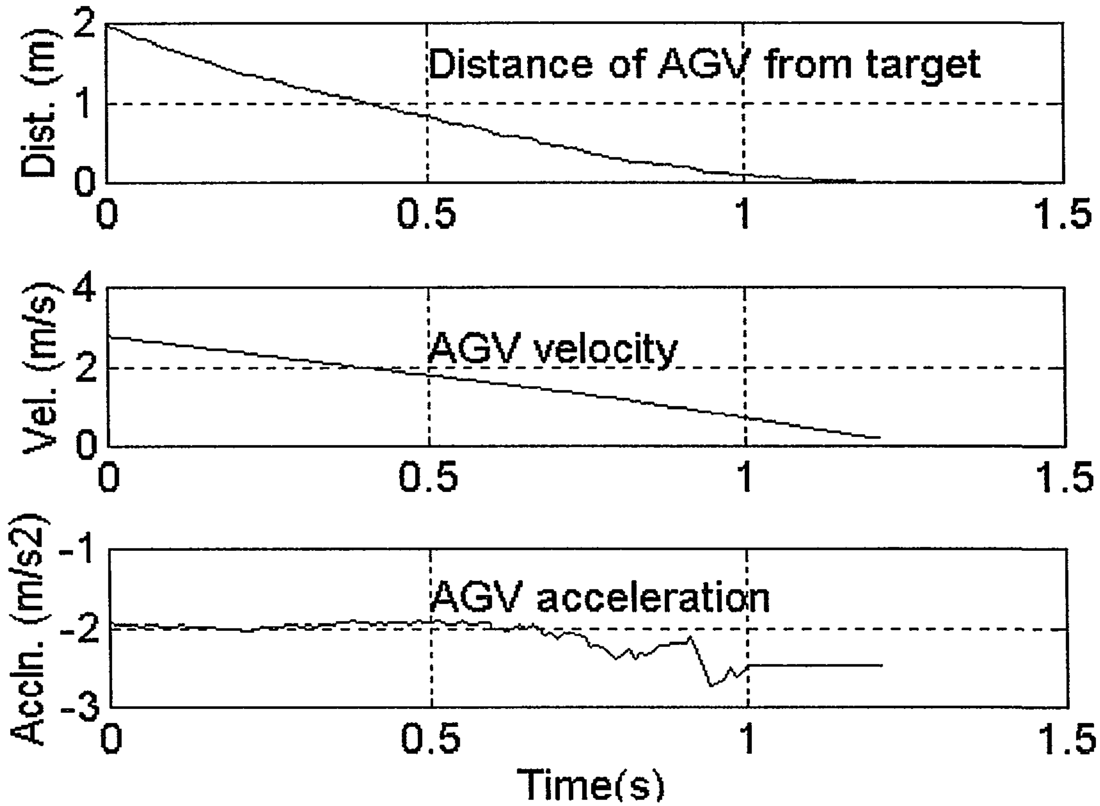

Figure 7.12 Simulation of adaptive positioning control

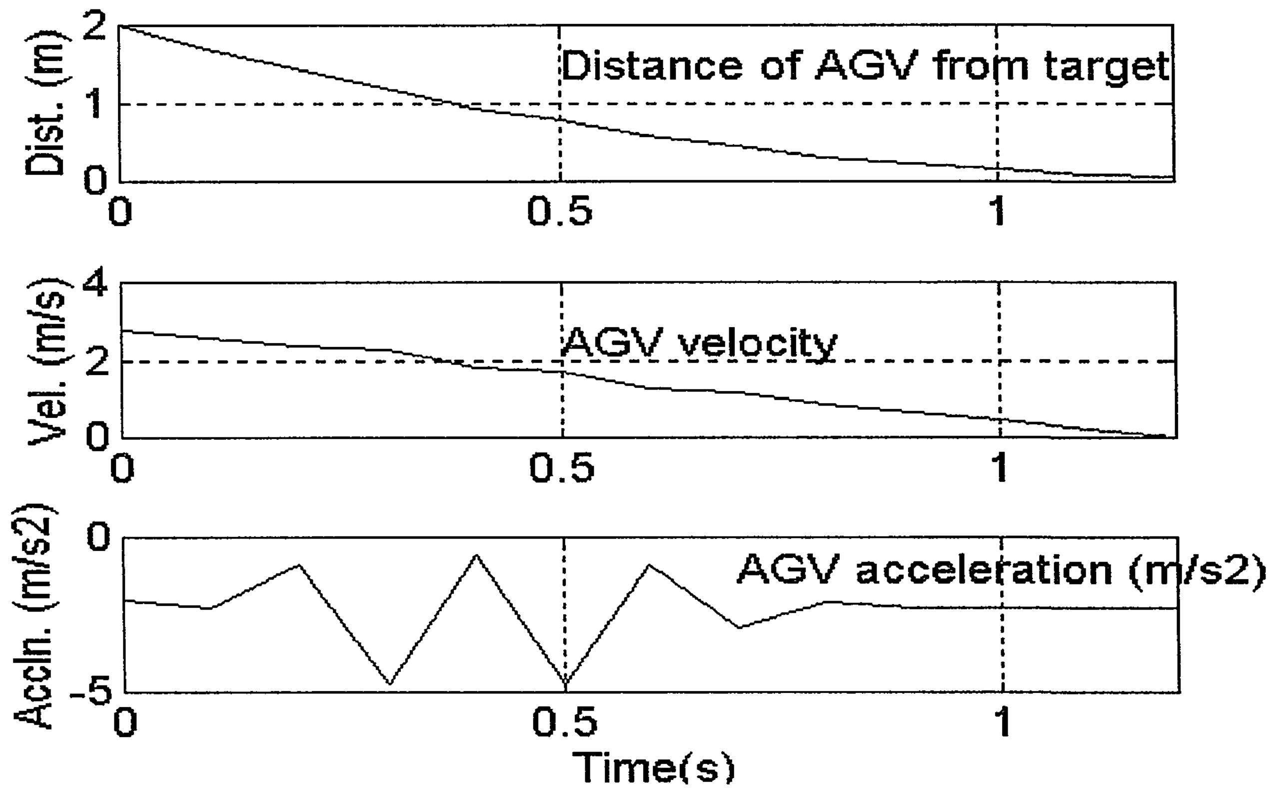

Figure 7.13 Simulation of fuzzy positioning control

TRANSIENT AND STEADY STATE SIMULATION OUTPUT

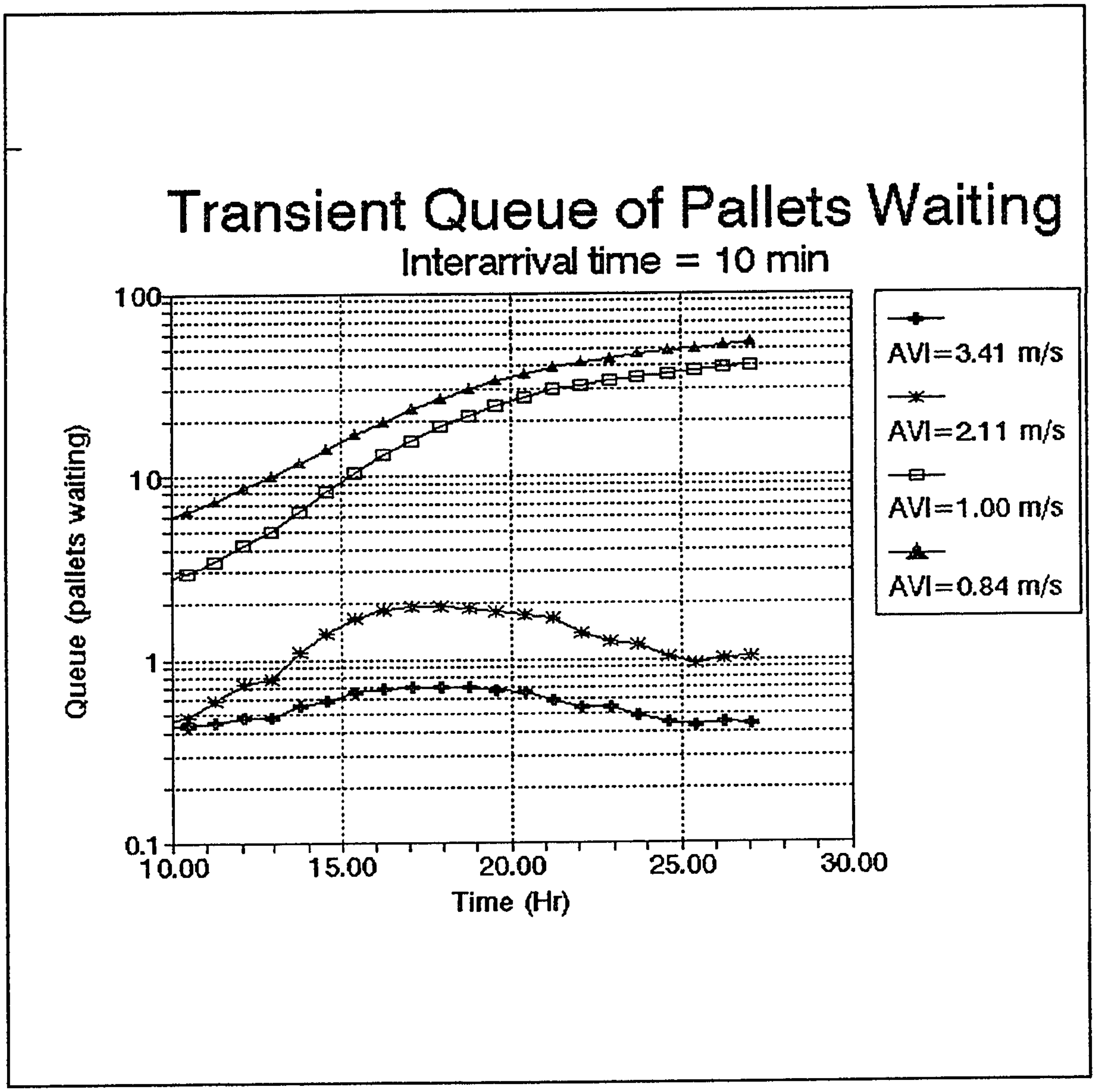

Figure 7.14 Transient response of [P] when interarrival time = 10 minutes

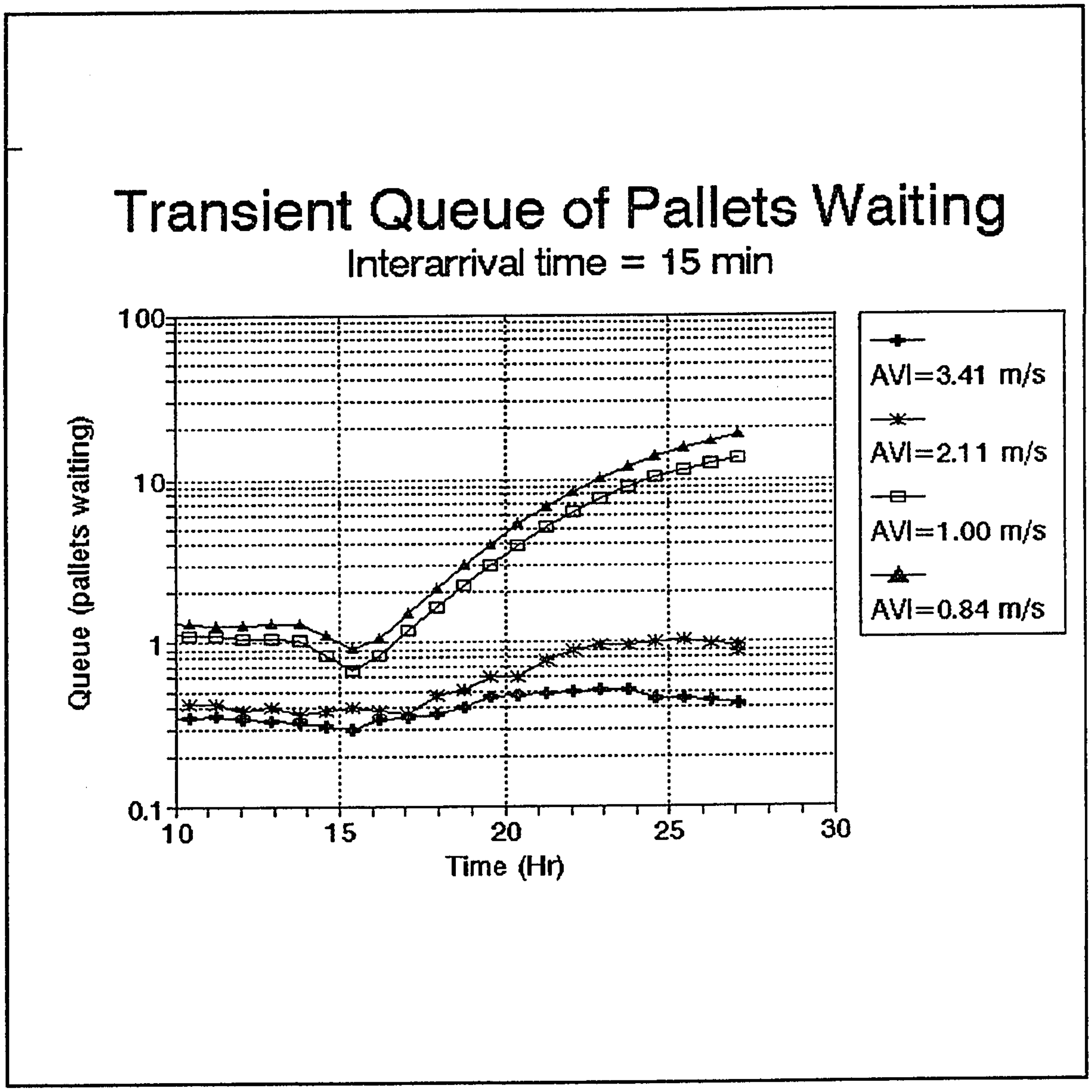

Figure 7.15 Transient response of [P] when interarrival time = 15 minutes

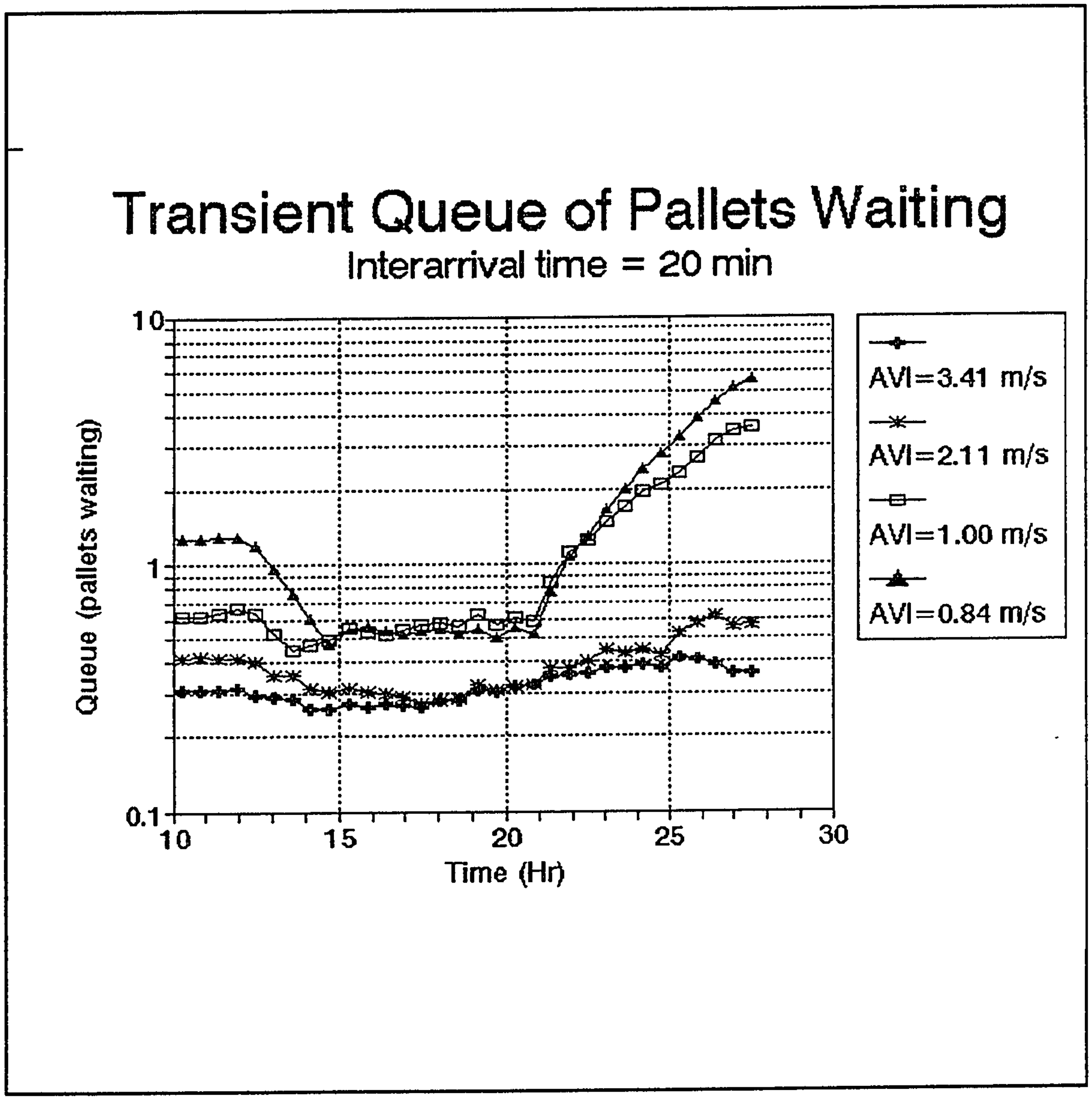

Figure 7.16 Transient response of [P] when interarrival time = 20 minutes

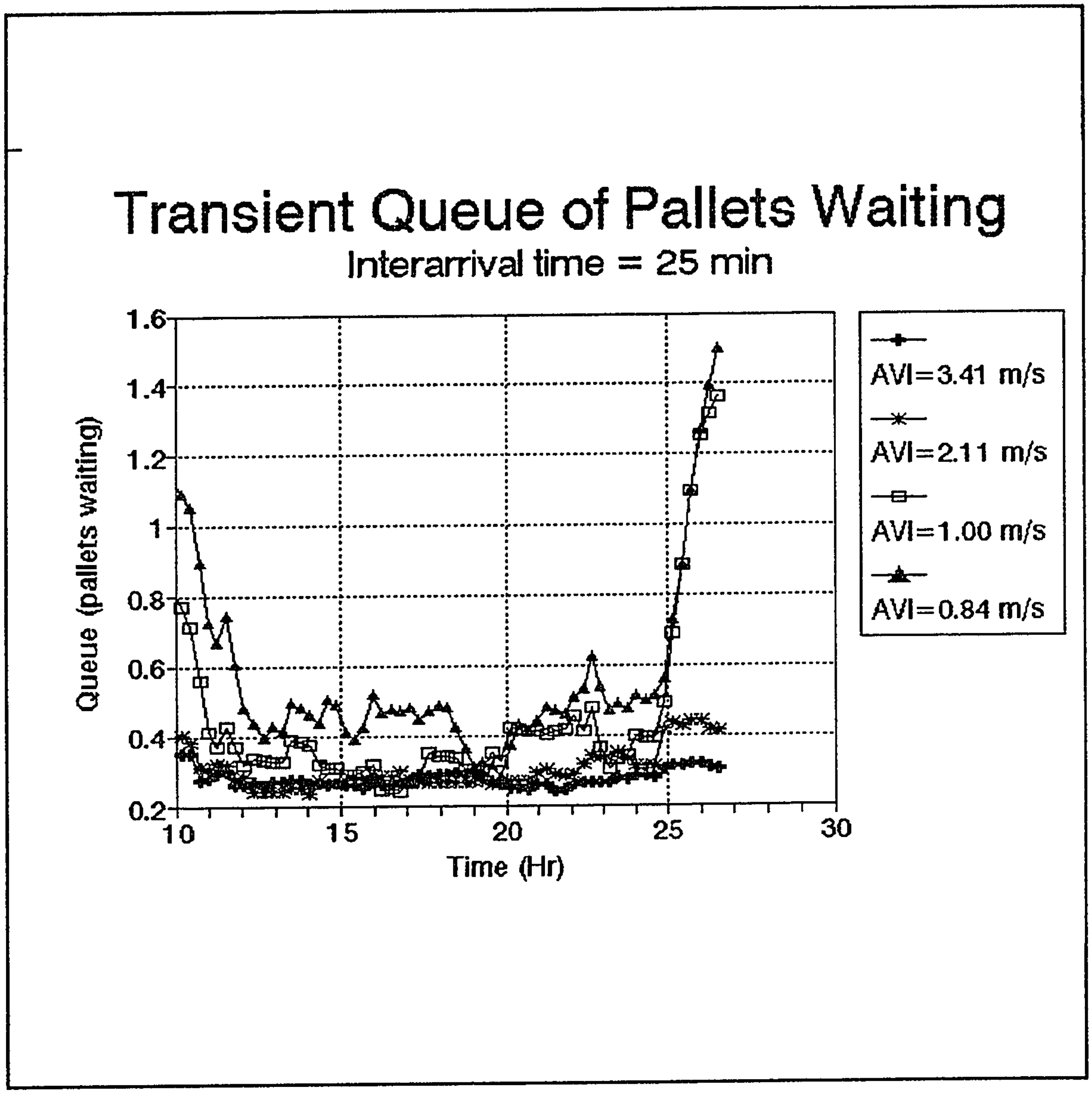

Figure 7.17 Transient response of [P] when interarrival time = 25 minutes

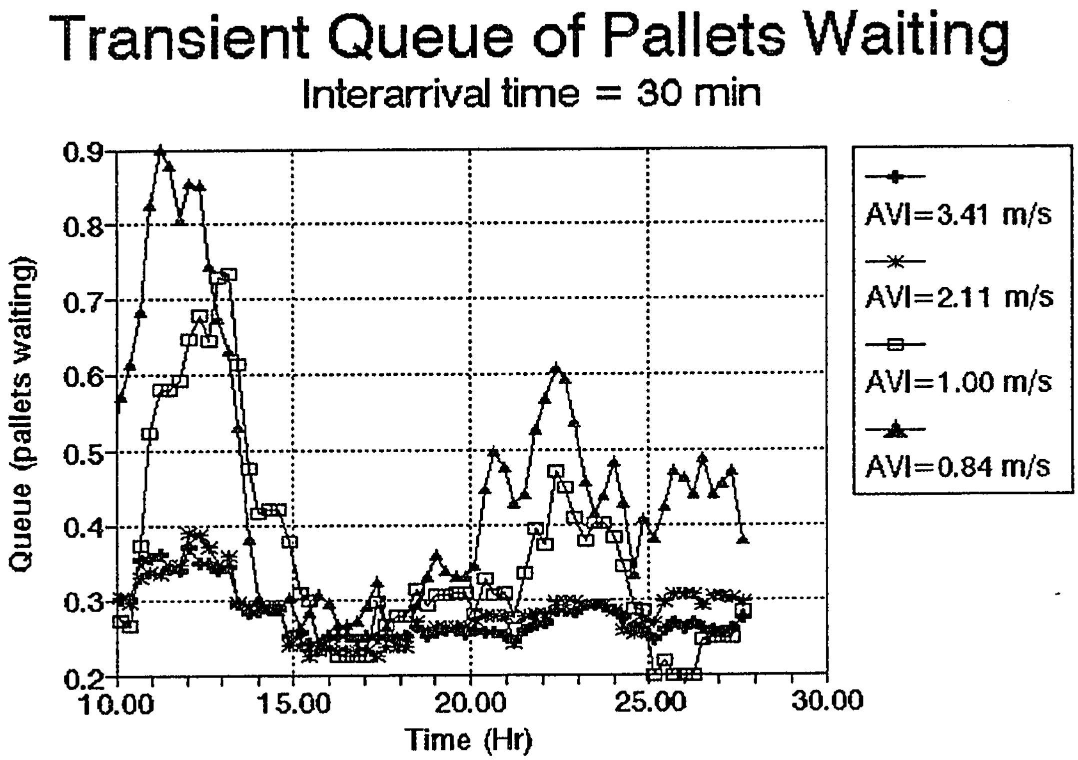

Figure 7.18 Transient response of [P] when interarrival time = 30 minutes

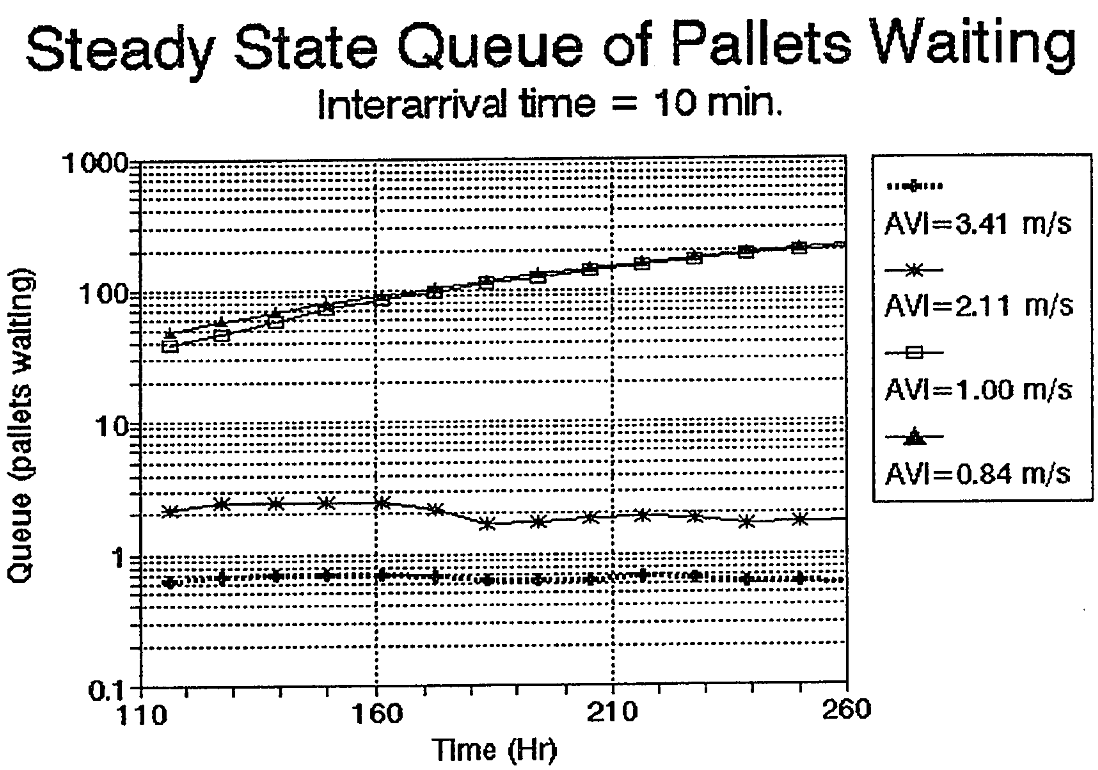

Figure 7.19 Steady state response of [P] when interarrival time = 10 minutes

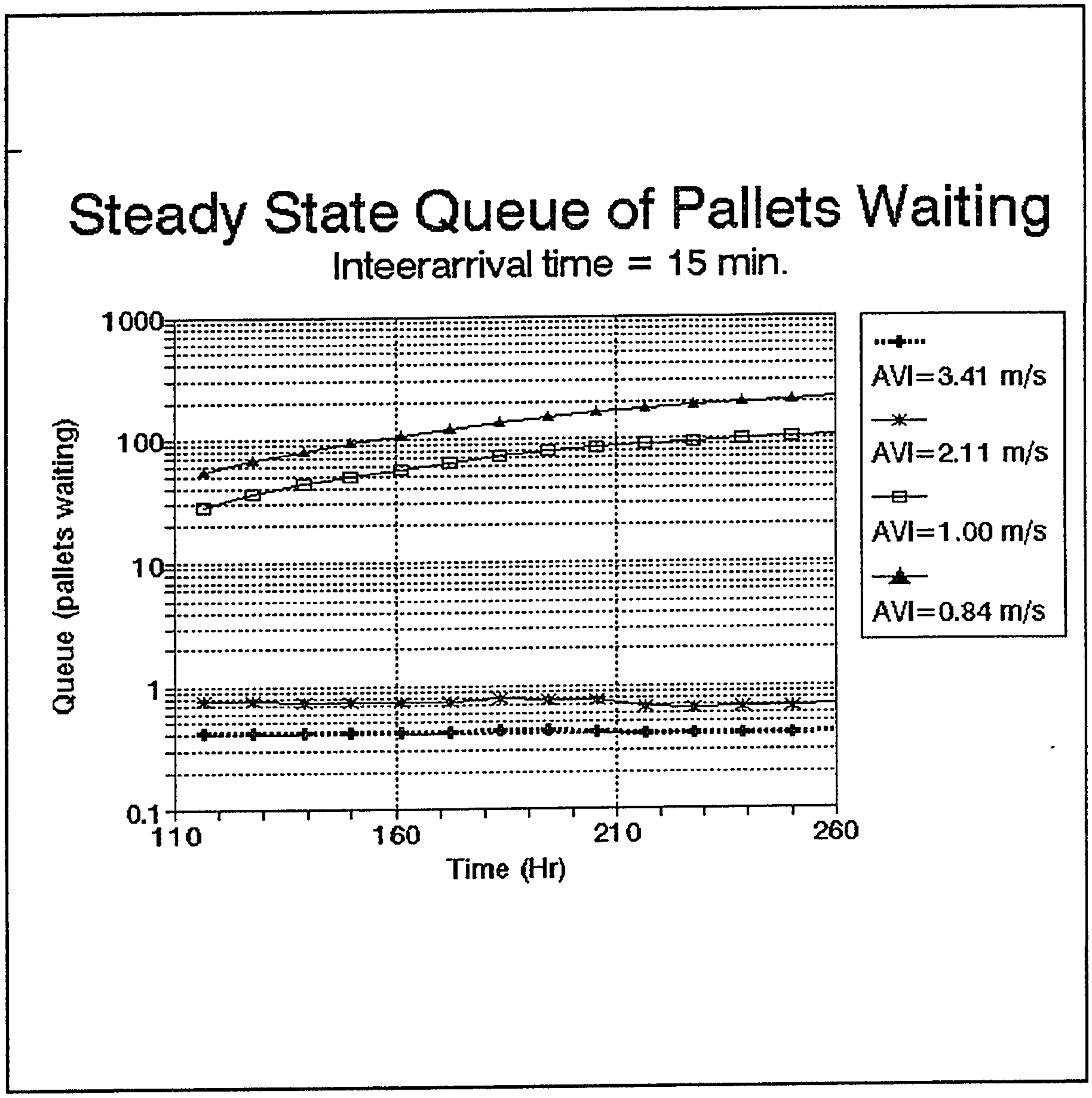

Figure 7.20 Steady state response of [P] when interarrival time = 15 minutes

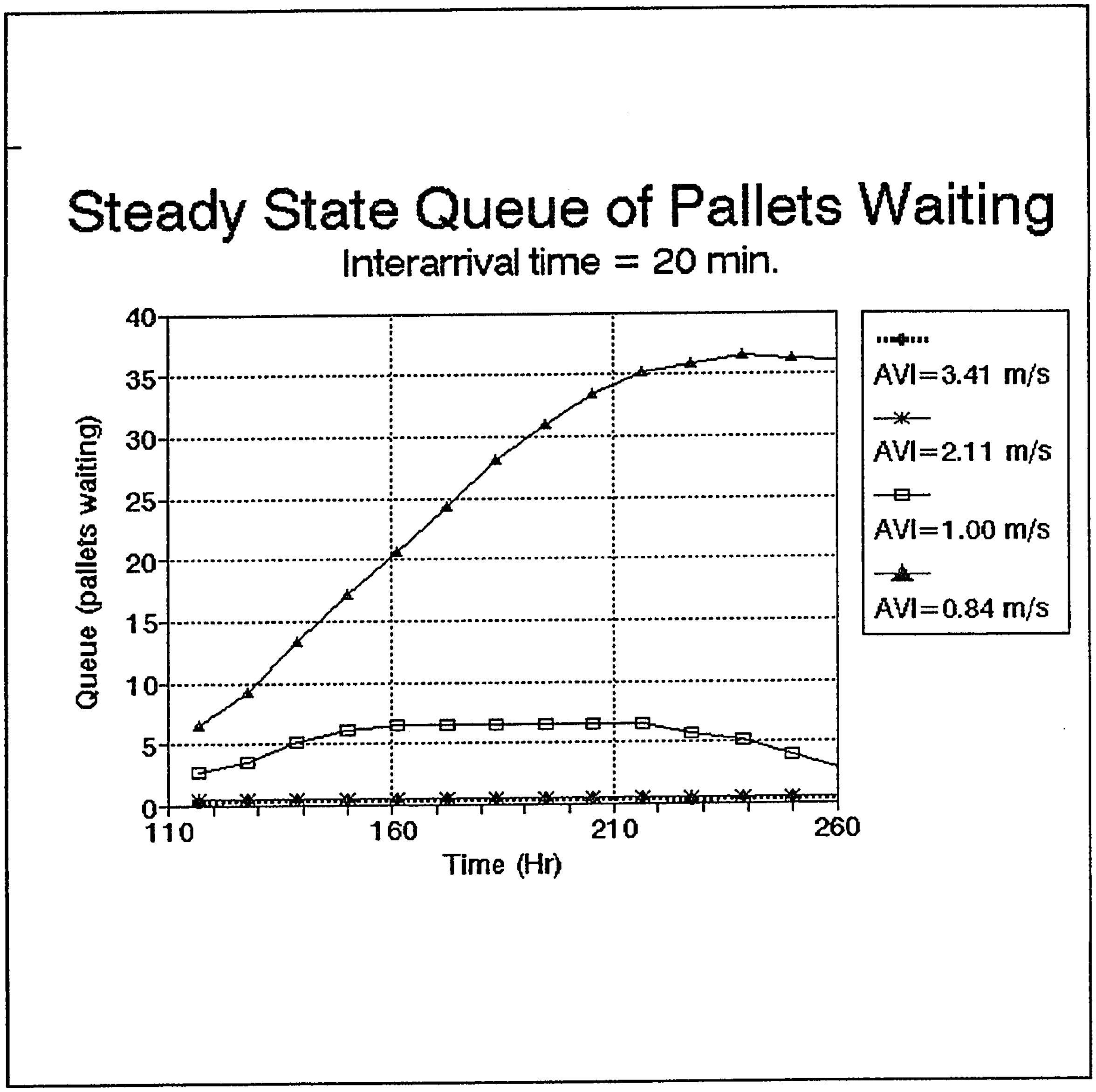

Figure 7.21 Steady state response of [P] when interarrival time =20 minutes

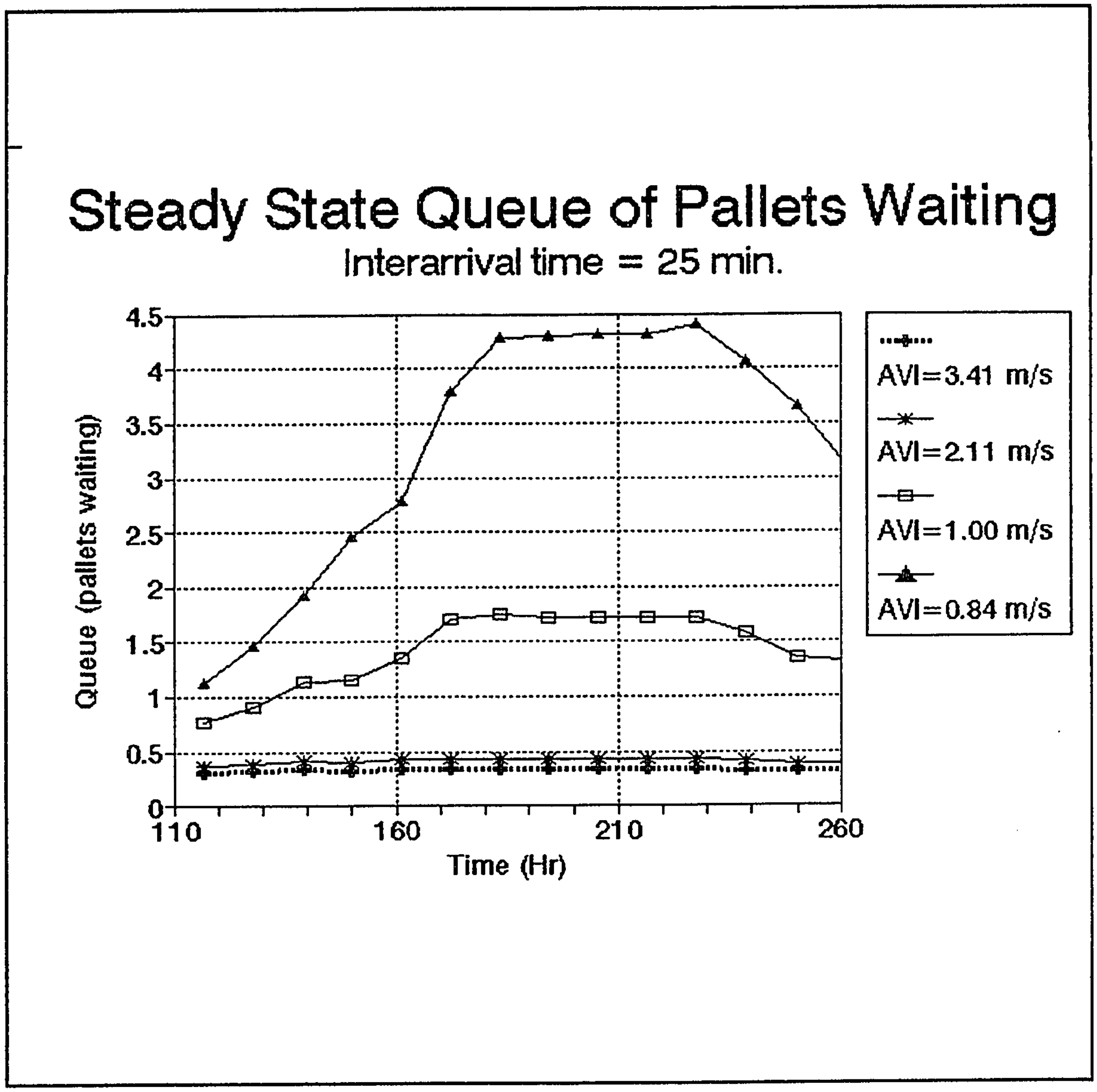

Figure 7.22 Steady state response of [P] when interarrival time = 25 minutes

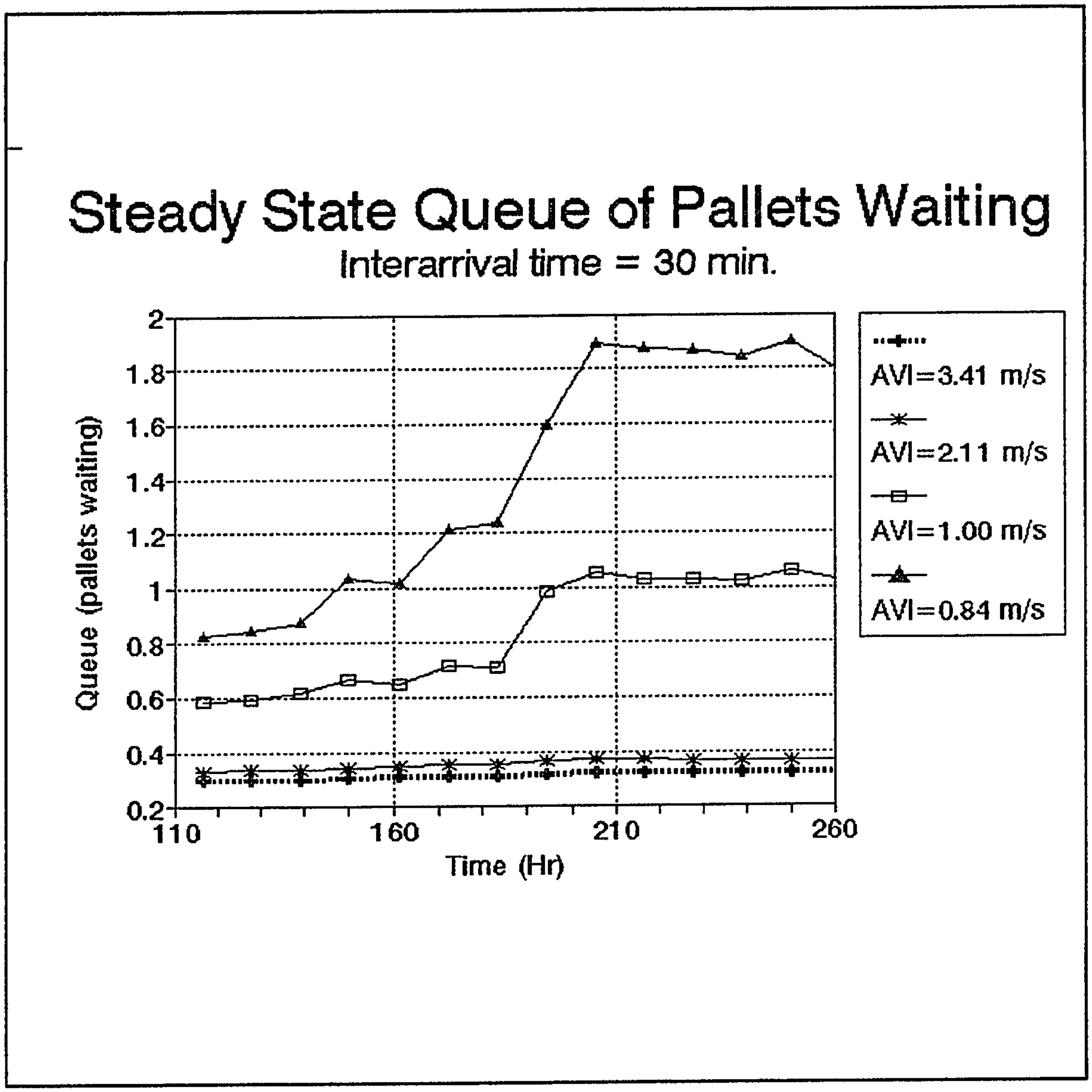

Figure 7.23 Steady state response of [P] when interarrival time = 30 minutes

LINK VELOCITIES AND AVI VALUES IN TABULAR FORM

TABLE 7.1 AGV path link velocities (no load)

First row entry: Power limited velocity (Power=15kW). Abbr:PLV
Second row entry: Maximum commercial AGV velocity. Abbr:CV
[v_1, v_2, v_3 = Initial, maximum and final velocity respt.
d = Length of link]

Link		v_1 (m/s)	v_2 (m/s)	v_3 (m/s)	time (s)	d (m)
1	PLV	0	10	2.38	1.67	2
	CV	0	1	1	2.34	
2	PLV	2.38	2.79	2.79	1.45	4
	CV	1	1	1	4	
3	PLV	2.79	10	3.13	5.19	25
	CV	1	1	1	25	
4	PLV	3.13	3.13	3.13	1.59	5
	CV	1	1	1	5	
5	PLV	3.13	10	0	5.92	21
	CV	1	1	0	21.31	
6	PLV	0	10	3.13	6.08	21
	CV	0	1	1	21.34	
7	PLV	3.13	3.13	3.13	1.59	5
	CV	1	1	1	5	
8	PLV	3.13	10	2.79	2.15	8
	CV	1	1	1	8	
9	PLV	2.79	2.79	2.79	1.43	4
	CV	1	1	1	4	
10	PLV	3.13	3.13	3.13	1.27	4
	CV	1	1	1	4	
11	PLV	3.13	3.13	3.13	1.27	4
		1	1	1	4	

TABLE 7.2 Average velocity index (avi) values for AGV

{AVI values are presented in (C) corresponding to time-distance values obtained from (A) and (B) below. Data in part (A) is obtained from simulation results of positioning control presented in figures 7.12 and 7.13. Data in part (B) is calculated from table 7.1.}

(A)
Time taken to travel link 1a (distance of 2 m during AGV positioning) under three types of control.

		Time (s)	Distance (m)
Fuzzy Control	(FC)	1.2	2.0
Adaptive Control	(AC)	1.2	2.0
No Control	(NC)	20.0	2.0

(B)
Time taken to travel across all the links in the network when moving at power limited velocities (PLV) and at maximum velocity of commercial AGV (CV).

		Time (s)	Distance (m)
Power limited velocity	(PLV)	29.61	103.0
Commercial AGV velocity	(CV)	103.99	103.0

(C)
Average velocity indices (AVI) corresponding to distance divided by travel time found from the combination of positioning control (rows 1,2 and 3) and power / velocity limited travel times (rows 1 and 2)[from (A) and (B) above].

AVI (No load, m/s)

	AC/FC	NC
PLV	3.41	2.11
CV	1.00	0.84

QUEUE LENGTHS AND ZERO WAITING PROBABILITIES IN MODIFIED NETWORK - RESULTS OF QUEUEING THEORY ANALYSIS

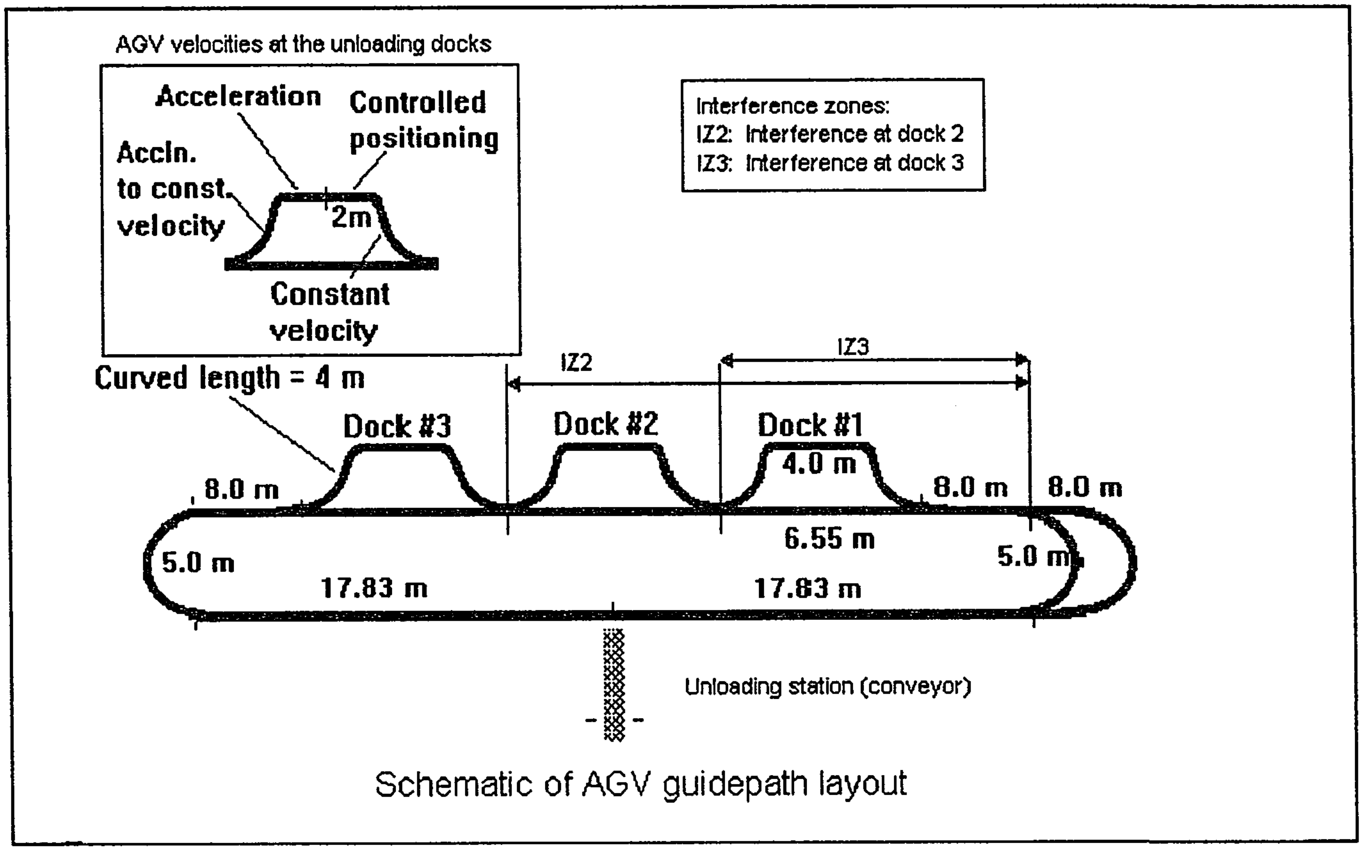

Figure 7.24 AGV path in a distribution centre at the unloading docks

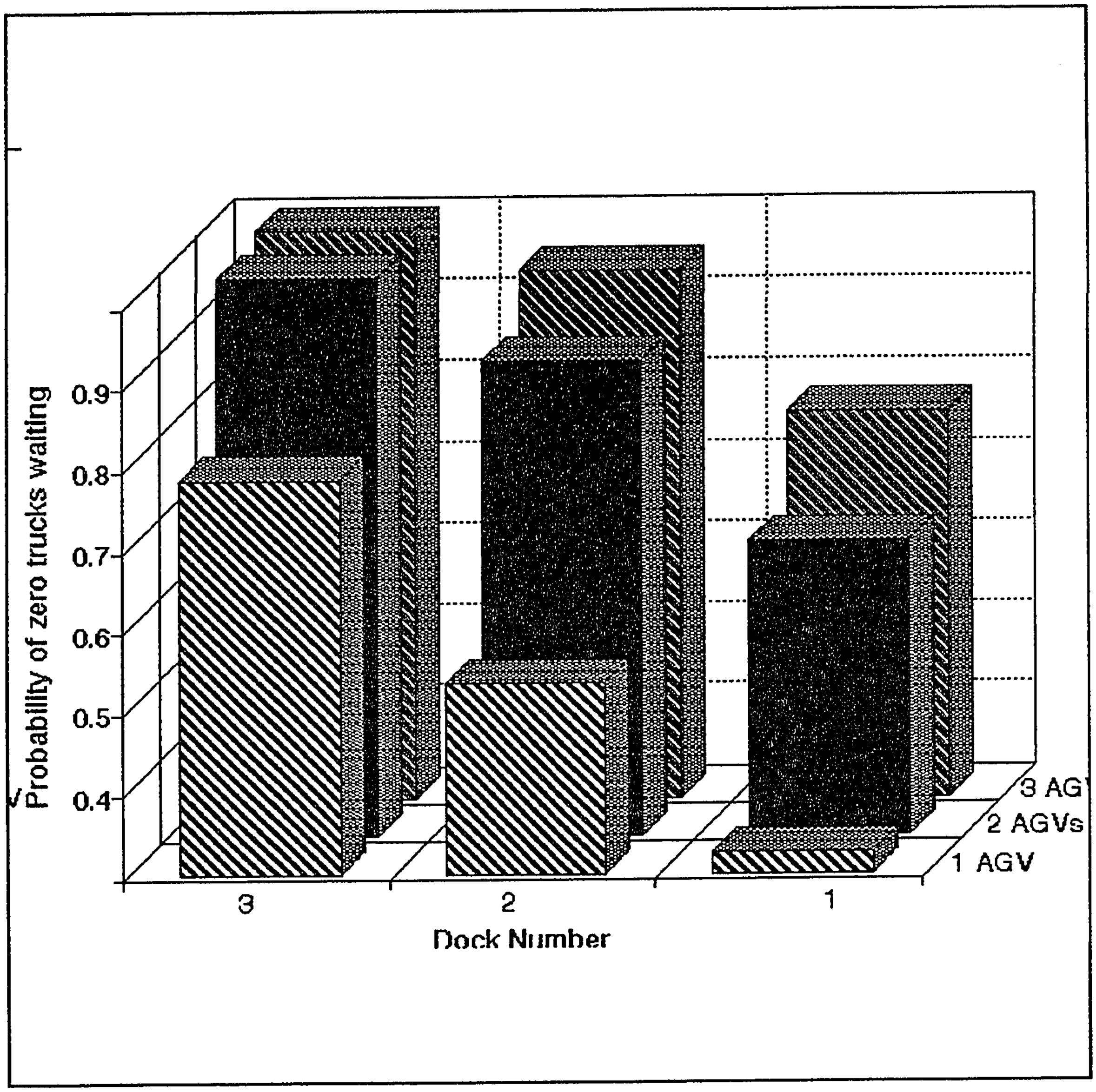

Figure 7.25 Trucks (each with 10 pallets) waiting at various docks

TABLE 7.3 Situation matrix describing states

# of AGVs	Trucks waiting at dock #		
	1	2	3
1	S_{11}	S_{12}	S_{13}
2	S_{21}	S_{22}	S_{23}
3	S_{31}	S_{32}	S_{33}

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$ Situation matrix:

TABLE 7.4 Probability of zero waiting and length of queue

Number of AGVs	Dock number (j)			
		1	2	3
1	P_0	0.324	0.533	0.784
	L_q	0.702	0.203	0.029
2	P_0	0.662	0.883	0.986
	L_q	0.086	0.007	0.001
3	P_0	0.774	0.948	0.997
	L_q	0.032	0.001	3.0E-6

$P_{0\ i,j}$ = Probabilty of zero waiting for situation $S_{i,j}$.

$L_{q\ i,j}$ = Expected length of queue (trucks waiting) for situation $S_{i,j}$.

$P_{0\ i,j}$ = $1-\lambda_j/\mu_{i,j}$.

λ = Expected value of interarrival rate {6 trucks / hr. at dock 1}.

λ_j = $\lambda_{j-1}*1-P_0$; j=2,3.

$\mu_{i,j}$ = Expected value of service time = 3600 / $T_{i,j}$

$T_{i,j}$ = $NP*T_{i,j}$ - Tj / N_i

NP = Number of pallets in each truck (10).

N_i = Dock number (1,2 or 3).

T_j = AGV travel time around network when servicing dock "j."

T_j^* = AGV travel time on link parallel to "staging link."

L_q = $\rho^2/\{2(1-\rho^2)\}$.

ρ = λ/μ.

8.0 DISCUSSION

8.1 Feasible AGV velocity

The velocity of the AGV is subject to dynamic constraints, and the need for accurate positioning. Velocity profiles have been generated for each segment of the guidepath and an "Average Velocity Index" (AVI) for the AGV guidepath is calculated as the quotient of the total distance travelled and the time required to travel the distance. The constraints taken into account are:

8.1.1 The maximum torque available

Acceleration depends on the torque delivered by the AGV. It is assumed that the drive wheels are powered by an electric motor, which delivers a constant torque over the speed range from 0 to 10 m/s. For constant torque electric motors, the acceleration remains almost constant as the speed changes.

8.1.2 A maximum "safe" velocity

Assuming that the motion of the AGV is adequately modelled using Newton's laws of motion, the velocity reaches a maximum somewhere in the middle of straight links. A limit of 10 m/s (38 Km/hr) is set to ensure safety. In commercial AGVs, the maximum average velocity for any link is less than 25% of this limit.

8.1.3 The tendency to topple while travelling along a curved path

The AGV slips easily normal to the direction of travel especially when the radius of curvature is small. At high values of the coefficient of friction, the tendency to topple limits the tangential velocity when the centre of gravity is significantly higher.

8.1.4 The tendency of the wheels to slip

While acceleration or braking is taking place, the force generated should not exceed the product of the normal reaction force of the AGV and the coefficient of friction. Also, the radial force generated when the AGV goes around a corner should not exceed the product of the normal reaction force and the coefficient of friction. Exceeding this force causes the AGV to slip laterally while rounding a corner.

A number of AVI values are obtained corresponding to moving the AGV at high and low velocity, and employing various positioning methods. The effect of the positioning method (adaptive control/fuzzy logic control/no control) has comparatively little effect on the AVI. This would not be the case, however, when repeated positioning moves are required, and t lesser positioning time when using positioning control (as compared to "creep feed" positioning) will result in significantly faster average AGV velocities.

Dynamic constraints affect the "service time" of the AGV. The effect of velocity change while going around curves is comparatively small in a network where the AGV spends most of it's travel time on straight links and on positioning. The maximum torque, however, has a significant effect on the velocity profiles along straight links. Considering the original network, depicted in **Figure 3.2**, the influence of torque on the service time is examined. The velocity profiles change as described.

8.2 Constrained velocity profiles

The velocity profile of an AGV on the network shown in **Figure 3.2** changes with AGV torque. Link #3 is considered as an example for a detailed discussion. The initial and final velocities of the AGV going into and exiting from the link are 2.79 and 3.13 m/s, because of the toppling and friction constraints while going around the curved paths immediately before and after link #3. These numbers are obtained from a consideration of toppling and sliding constraints. The centre of gravity of the AGV is taken as 0.8 m. A higher centre of gravity of 0.95 m is assumed at the loading docks, to improve the safety margin in the dock area. The velocity constraints in case of the curved links next to the dock, are depicted in **Figures 8.1 and 8.2**. The AGV velocity profile on link #3 is depicted in **Figure 8.3**. The acceleration of the AGV is calculated based on the assumption that the AGV moves with the same torque as a commercial sideload AGV, capable of carrying loads of 1200-1400 Kg. The BT F-30/40 sideload forklift (Specifications in the Appendix) is a typical example. This forklift is a 15 kW vehicle capable of uniform acceleration to 4 m/s. The torque generated is calculated as follows:

$$\begin{aligned}\tau &= r_w \\ &= \frac{P}{v} \times r_w \\ &= \frac{15000}{4.00} \times 0.10 \\ &= 375\ N.m\end{aligned}$$

τ = *Torque N.m* $\quad r_w$ = *Radius of drive wheel (m)*

P = *Power (kW)* $\quad v$ = *Velocity* $(\frac{m}{s})$

Since the torque is assumed to remain constant with changing velocity, the acceleration of the AGV is constant and equal to:

$$\frac{\tau}{r_w \times m_{AGV}}.$$

Figure 8.4 depicts the velocity profile of the AGV along the same link when the power is raised so that the acceleration of the AGV is limited by friction only. A friction coefficient of

0.8 between the wheels of the AGV and the floor is assumed. The corresponding torque is assumed as:

$$\tau = m \times g \times 0.8 \times r_w$$
$$= 2633 \times 9.81 \times 0.8 \times 0.100$$
$$= 2070 \ N.m$$

The AGV has to enter the next link at a velocity less than or equal to 3.13 m/s, which is the toppling / friction constrained maximum velocity, and therefore, when the available torque is increased, the AGV is required to decelerate after accelerating to a maximum permitted velocity of 10 m/s. The distance "s" remaining at the point where the AGV commences to slow down is a function of the current velocity "u", the final velocity, "v", and the required deceleration "a" in accordance with the relation:

$$s = \frac{v^2 - u^2}{2 \times a}$$

Subject to the constraint that $a < \mu g$, where the friction coefficient, μ, equals 0.8, and the acceleration due to gravity, "g" equals 9.81. Thus, the AGV starts decelerating when the distance required to slow down from its current velocity equals the distance remaining on the link. Apart from the toppling constraint and the friction constraint, which guards against slip while going around a curve or accelerating / decelerating along a straight link, there is a constraint on the maximum AGV velocity, for reasons of safety. This value is arbitrarily selected as 10 m/s (36 km/hr), and the AGV is not allowed to exceed this velocity at any point.

It is interesting to notice how the time required by the AGV to travel around the loop changes as the torque is increased in equal increments of 375 N.m, starting from 375 N.m. The torque and corresponding travel times are presented in **Figure 8.5**. The travel time evidently does not scale linearly with torque, and, as seen in **Figure 8,6**, savings in the time required to go around the network decrease for higher values of torque. Various constraints have to be satisfied while the AGV is in motion. The maximum velocity constraint of 10 m/s imposed on straight links and the 2.79 m/s or 3.13 m/s[1] (depending on the radius of curvature), constitute the velocity / toppling constraints. From **Figure 8.4** it is observed that the maximum velocity constraint of 10 m/s comes into effect on link #3 when the AGV is accelerating and decelerating at friction limited power, but not when the power considered is 15 kW, which is a typical commercial AGV specification for application in pallet transport operations.

The velocity constraint while going around a curved path is a function of both slipping and toppling. From **Figures 8.1 and 8.2** it is observed that for the particular AGV under consideration, toppling governs the curve velocity constraint unless the friction coefficient is quite low, when friction, which constrains radial slip, is the governing factor. As expected, a change in the height of the centre of gravity, or / and the wheelbase of the AGV has an influence on the diagram. For example, in **Figure 8.1**, the centre of gravity is at a height of 0.95 m. When this decreases to 0.80 m, the surface describing the velocity constraint would appear as in **Figure 8.2**. Friction becomes a factor when the floor is very slippery, or when the wheel base is very wide and the AGV attempts to negotiate a curve at a high velocity. This is clarified in **Figure 8.7**, where the height of the centre of gravity is kept at 0.8 metres and the width of the wheel base is increased from the current value of 1.25 m to 2.50 m. We observe here that toppling is no longer in factor for the range of variables considered, and friction governs the velocity constraint while the AGV negotiates curved paths.

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[1] This velocity depends on the radius of curvature, since radial slipping occurs when the centrifugal acceleration, v^2/r exceeds the product of the friction coefficient and gravitational acceleration, μg. Also, toppling may occur at higher velocities. These constraints are discussed in chapter 4.

8.3 Visual sensing

Autonomous operation of an AGV is difficult if the position of the pallets at the unloading docks is unknown. Currently, most AGVs material handling systems employ limits switches for positioning the AGV in front of a pallet. These are inexpensive devices and work very well if the position of the pallet is known fairly accurately. A method of visually sensing the position of the pallet with respect to the current position of the AGV is suggested in the thesis. The sensor consists of a ccd camera equipped with a wide angle lens and a halogen light source. A retro- reflecting target on the pallet is imaged by the camera. A very high contrast image is formed when the halogen light source is positioned close to the imaging lens. This image is captured by the ccd camera and stored in the form of a binary data file. This file was read in MATLAB, a mathematical computation software, and an intensity thresh holding operation was carried out.

The MATLAB code written by the author for the purpose of intensity threshholding the image provides the flexibility of reducing the size of the image file to suit accuracy requirements while predicting the target location. Threshholding can also be performed at various intensity levels. The location of the centre of gravity of the image is conveniently found by taking moments of the high intensity area about an axis. The influence of small areas of high intensity (noise) was comparatively small in the experiments, and the calculated target location was in very good agreement with the actual measured values. This sensor is therefore capable of providing accurate information about the target location with comparatively simple and rapid image processing. The vision sensor is a vital part of the autonomous material handling system, since one of the most complicated tasks of the human material handling equipment operator is quickly positioning the equipment before picking up the target pallet. Accurate identification of the target position is the first step in positioning the AGV prior to picking up the pallet load.

The advantage of a non-contact optical sensor for AGV positioning lies in the fact that the vision system constantly monitors the distance of the AGV from the pallet while the AGV is in motion. This is difficult to achieve with a mechanical sensor, which may be capable of reading distance at a particular position of the AGV. Positioning the AGV is difficult to achieve without a feedback mechanism, and therefore a mechanical sensor would constrain the AGV to move forward at a creep speed until the pallet is hit by limit switches or other mechanical sensors, in a much more time consuming process. Moreover, if the pallet is absent, considerable time may be lost in creeping forward and verifying that the pallet is not in the expected region. These particular problems will not arise with the optical sensor described. In case of obstruction, the AGV can transmit a message requesting manual intervention or teleoperation.

8.4 AGV Positioning

Once the location of the target is calculated, the acceleration, duration of acceleration, and deceleration of the AGV can be controlled so that it is positioned correctly when it comes to a stop. There is also the possibility of random error in the reading of the vision sensor, and in acceleration control. A simulation of possible positioning methods was performed with MATLAB code written by the author. It is assumed that the target position is retrieved at the rate of 10 images per second, and that the error between actual and calculated target location is normally distributed. Two cases are considered:

1. Adaptive control of AGV location by controlling deceleration.
2. Fuzzy logic based position control by controlling deceleration.

The simulation results provide an estimate of the time needed for positioning. The adaptive control method has one drawback in that it works only if the dynamics of the AGV can be accurately modelled. In the absence of an accurate model, a "model free" control method may need to be used. Therefore, a fuzzy logic control method is suggested and simulated.

In order to reduce time for the positioning operation, the AGV is kept in motion at the maximum velocity permitted while going around the curved link preceding link #1, and the deceleration of the AGV required to bring it to a stop in front of the target is calculated. It is noticed from the plots of AGV velocity and time needed for positioning (in chapter 7) that there is a considerable difference in travel time when it is moved at "creep velocity" until it reaches the target.

8.5 System performance

By controlling AGV velocity profiles while travelling around the network, using vision sensors and controlling AGV positioning, significant improvement in the time needed to travel around the network can be achieved. As revealed in **Figure 8.5**, the torque available may not be the most important factor in reducing travel times - rather, the maximum velocity at which the AGV is permitted to travel, and the mode of positioning (creep feed positioning using limit switches, or vision based adaptive / fuzzy control positioning) have a far greater effect on system performance as measured by travel time. Vision based control may prove to be more reliable by virtue of it's non-contact mode of operation. Simulation of positioning control provides evidence that the positioning methods proposed can be employed on an actual AGV.

The enhanced travel times are input into a simulation model to study transient behaviour of a single loop single AGV system. The steady state results indicate hat "safe" system parameters in the steady state results do not cause queue build up in the transient region, and therefore may be treated as feasible system parameters. An exhaustive list of system parameters which influence system behaviour are:
Arrival rate (of trucks carrying 10 pallets each)

AGV parameters

- Maximum AGV velocity
- AGV torque
- AGV centre of gravity
- AGV wheelbase
- AGV mass

Network parameters

- Curve radii
- Friction coefficient
- Number of links
- Link geometry
- Sequence of links
- Required starting, stopping and maximum link velocities

8.5.1 Steady state analysis of larger networks

A very interesting feature of the queueing analysis is the justification of the "building block" approach to extend the results of the simulation study to larger networks with more than a single AGV. The constraints imposed are that:

- The queue length at the steady state in dock #1 is the highest
- An "overflow" process transfers trucks to subsequent docks
- The maximum steady state queue length at dock #3 is not permitted to exceed 1 truck, as this would create the possibility of queue build up {since overflow occurs when the queue length exceeds 1}.
- The AGVs are assumed to travel in one direction only, and the maximum possible time lost due to interference is taken into account, for the sake of comparing results. The queue lengths at docks 2 and 3 therefore represent the maximum values of time

lost due to interference (not expected values), and the actual figures will be lower.

These conditions can be modified to permit larger steady state queue lengths as applicable. Since the transient region does not display drastic queue build-ups for "safe" situations, and since the probabilities of trucks waiting all depend on the probabilities of one dock and one truck, as shown in the previous chapter. While the "extended model" discussed is subject to certain constraints, it is quite significant that for a number of distribution centres where the "overflow" mechanism is valid, the model framework is directly applicable, thus opening up interesting possibilities of intelligent control with a strong link to AGV dynamics and visual sensing.

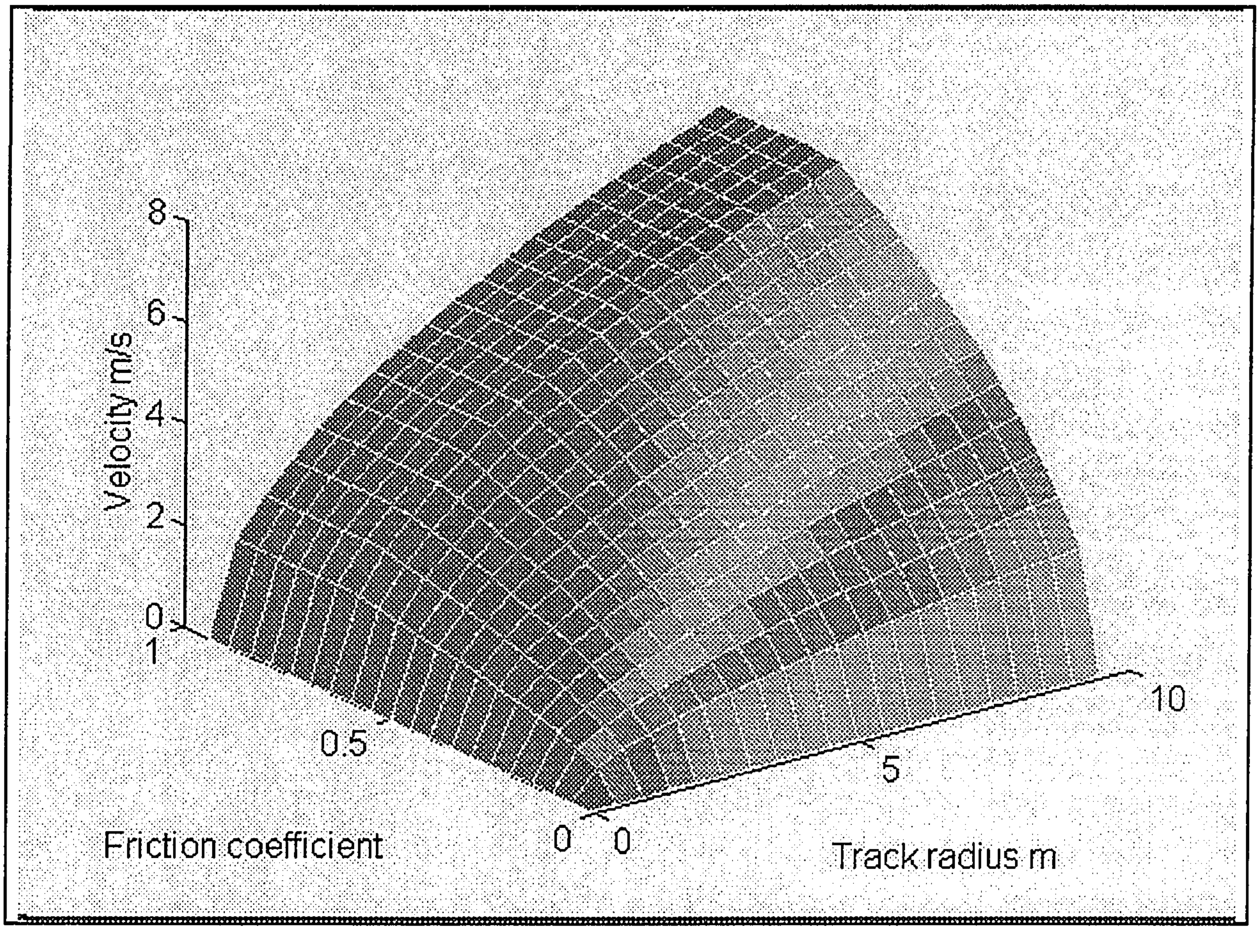

Figure 8.1 Velocity constraint for sliding or toppling with centre of gravity at 0.95 m, wheelbase=1.25 m.

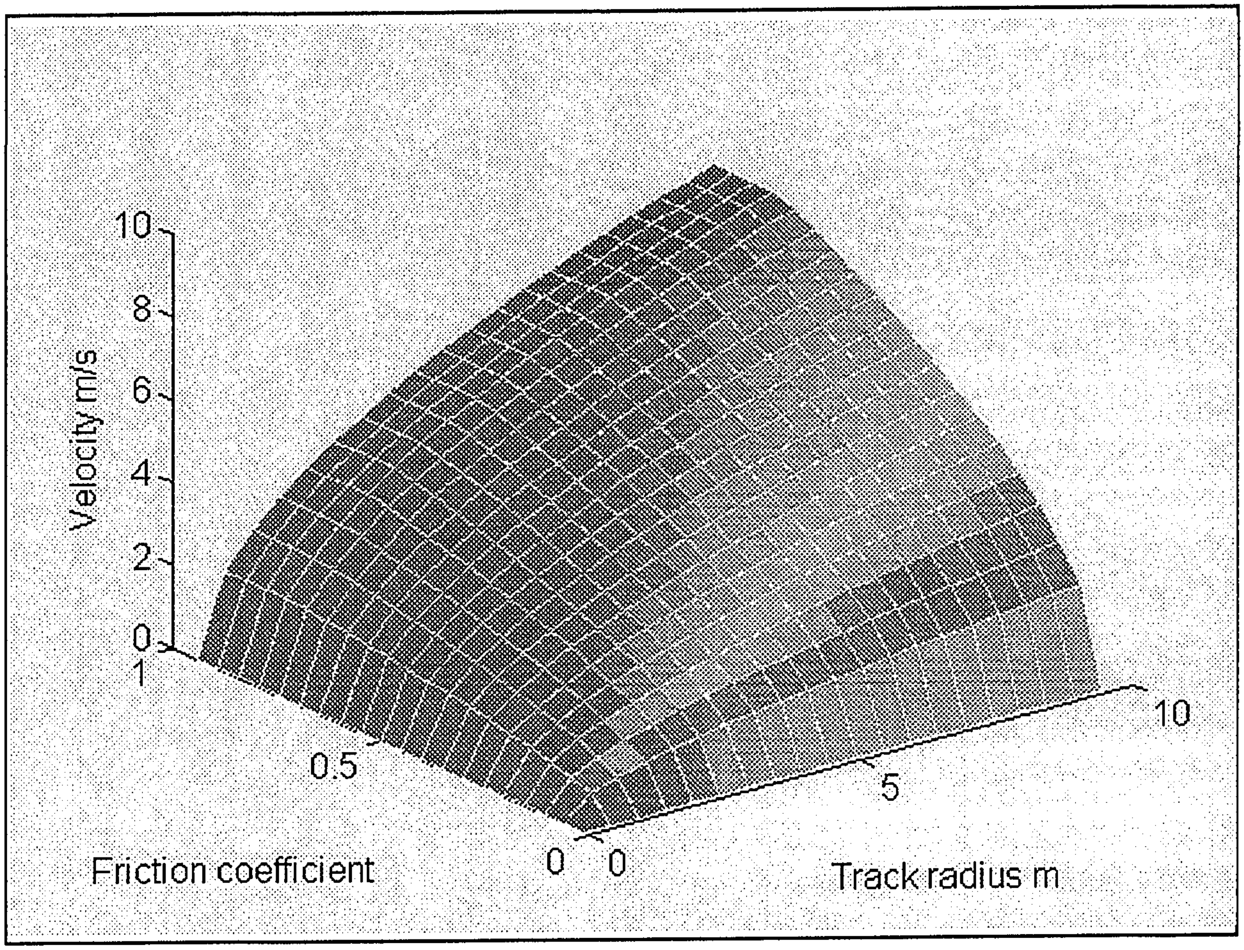

Figure 8.2 Velocity constraint for sliding or toppling with centre of gravity at 0.80 m, wheelbase=1.25 m.

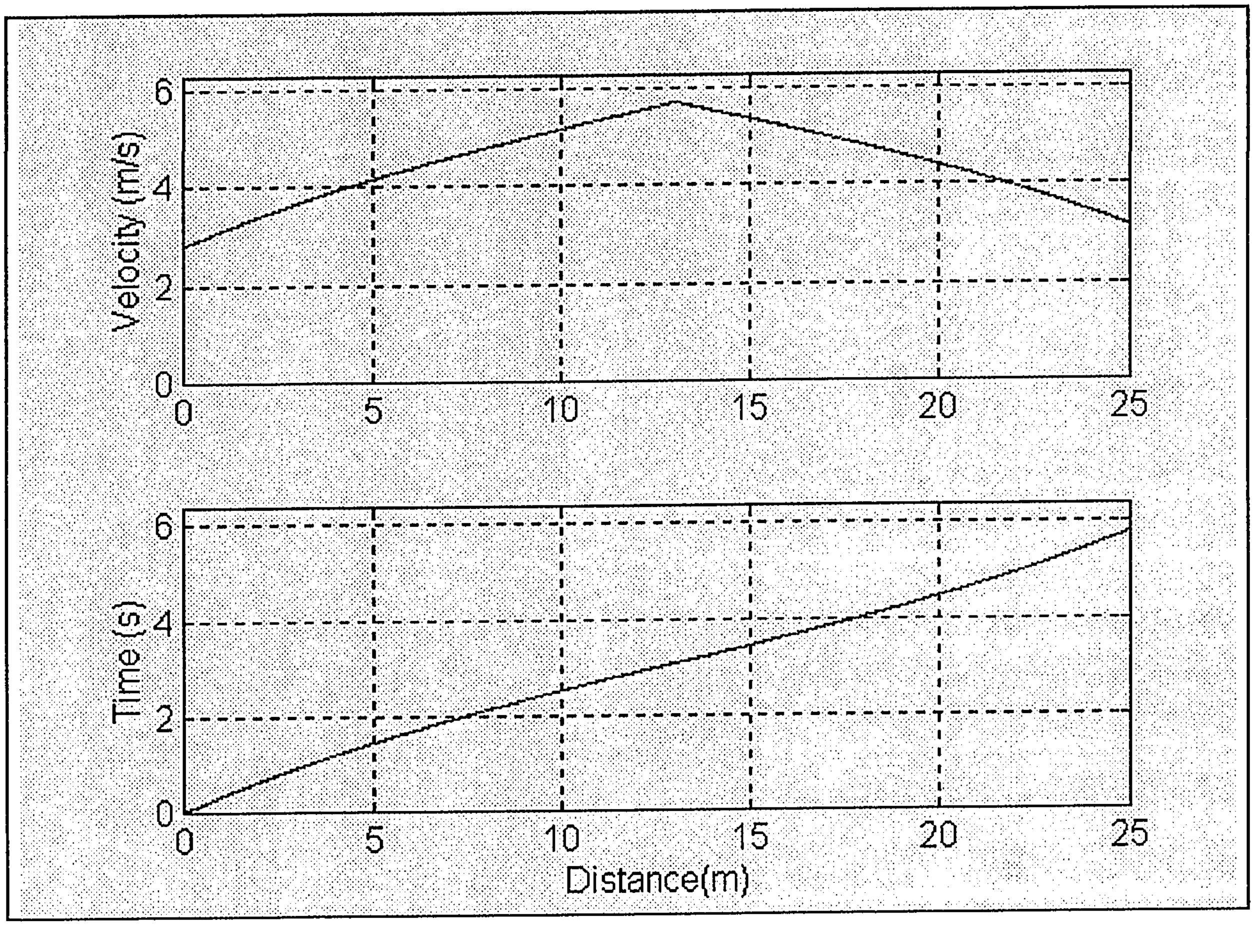

Figure 8.3 AGV velocity profile on link#3 (of network in Figure 3.2) - low torque

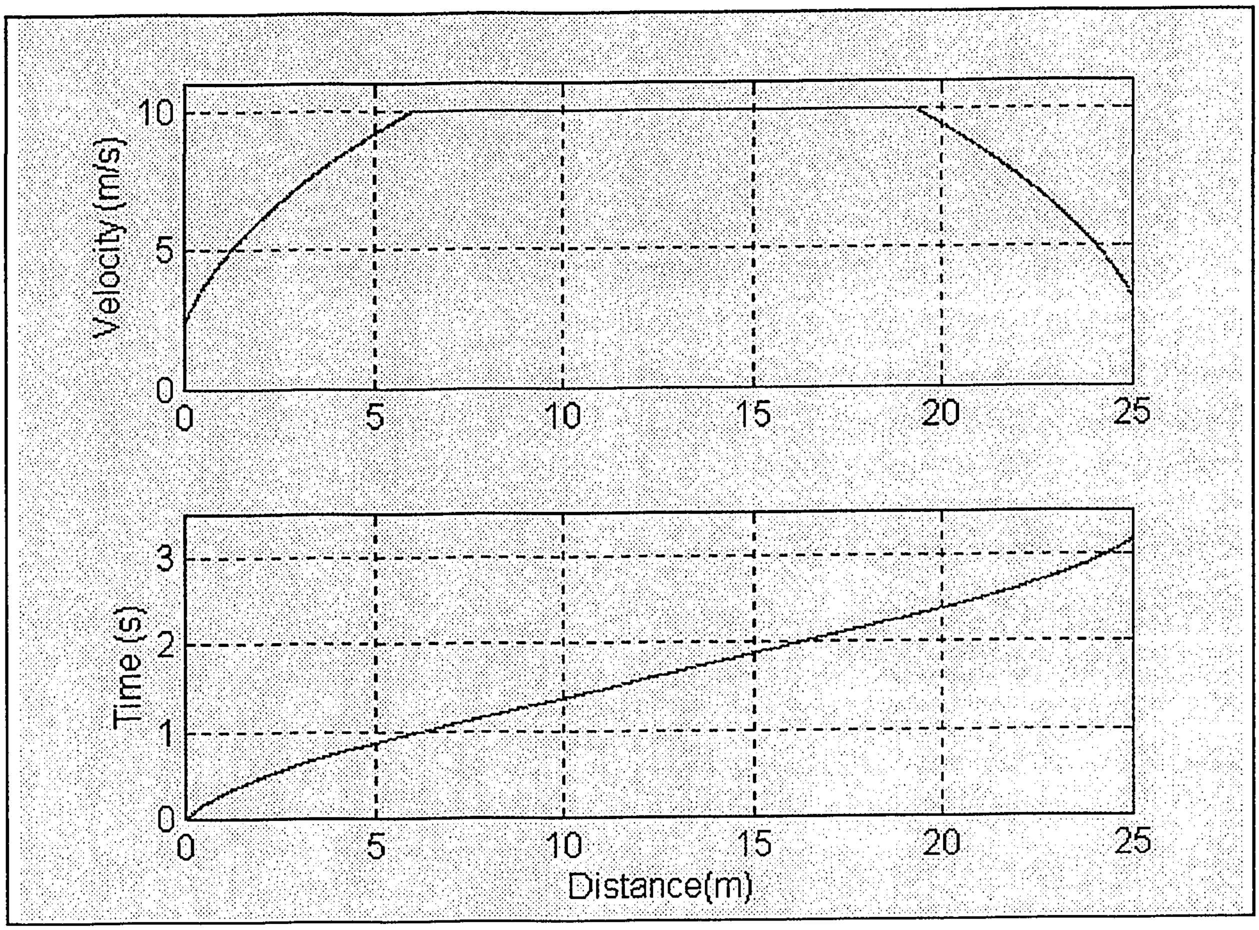

Figure 8.4 AGV velocity profile on link#3 (of network in Figure 3.2) - high torque

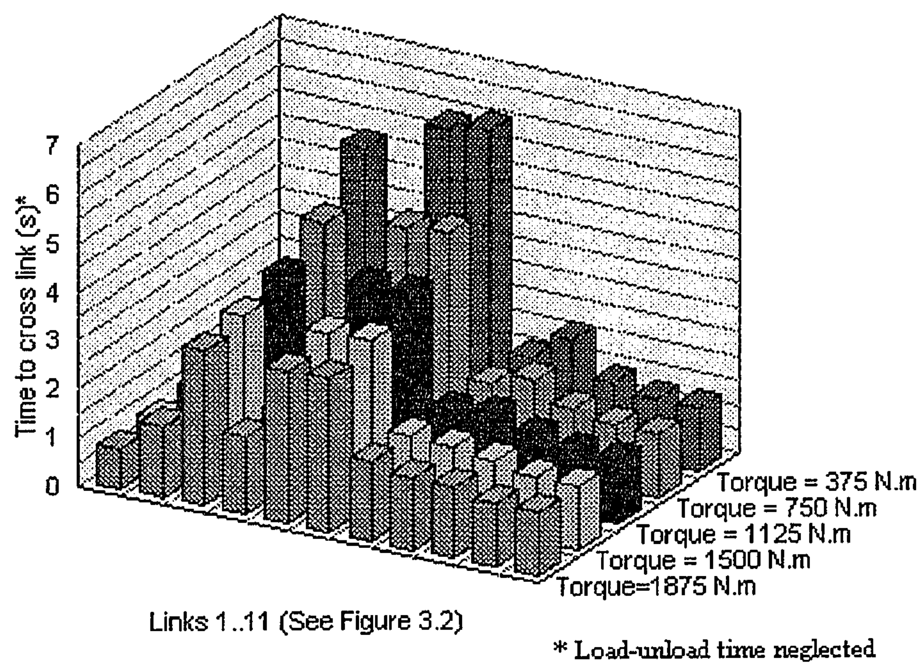

Figure 8.5 Travel times along the links of the network at different values of AGV torque. Load-Unload times have been neglected.

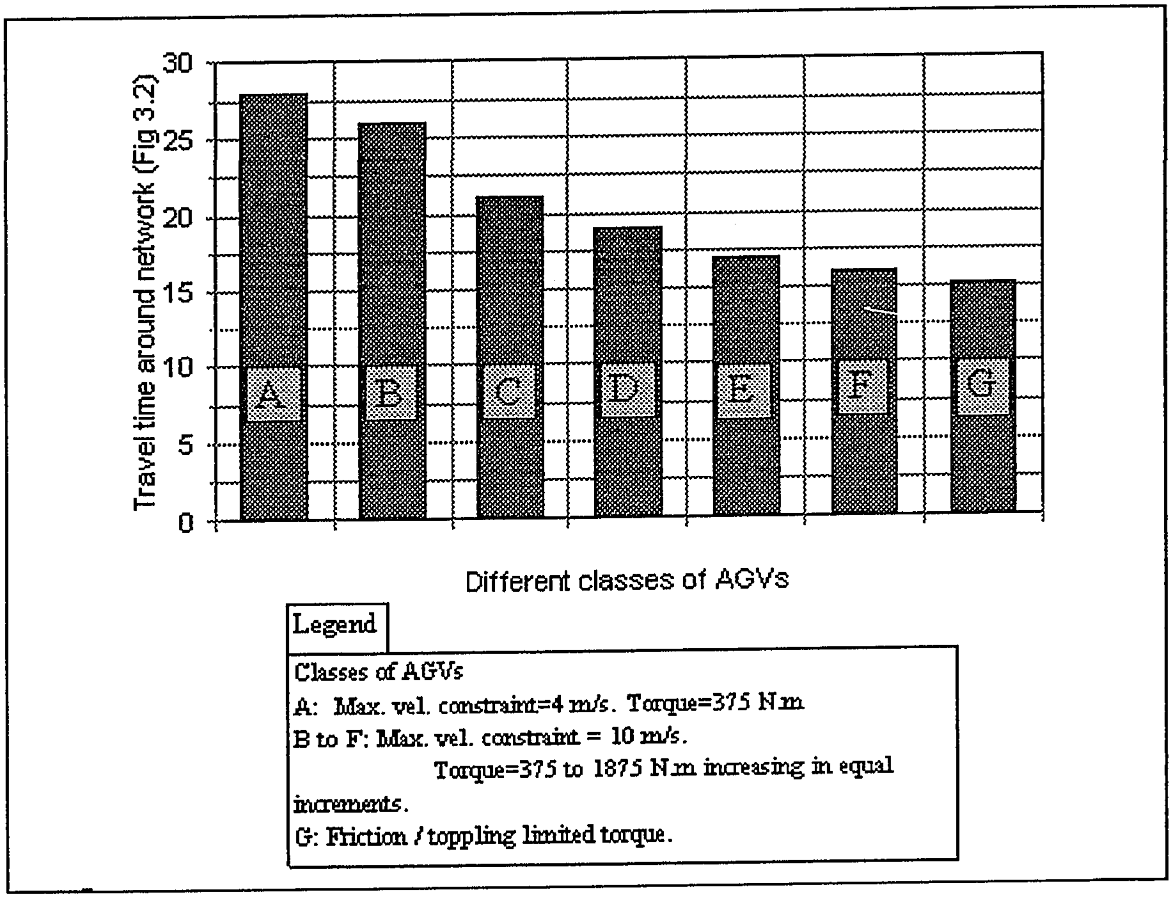

Figure 8.6 Travel time around the network as a function of AGV class

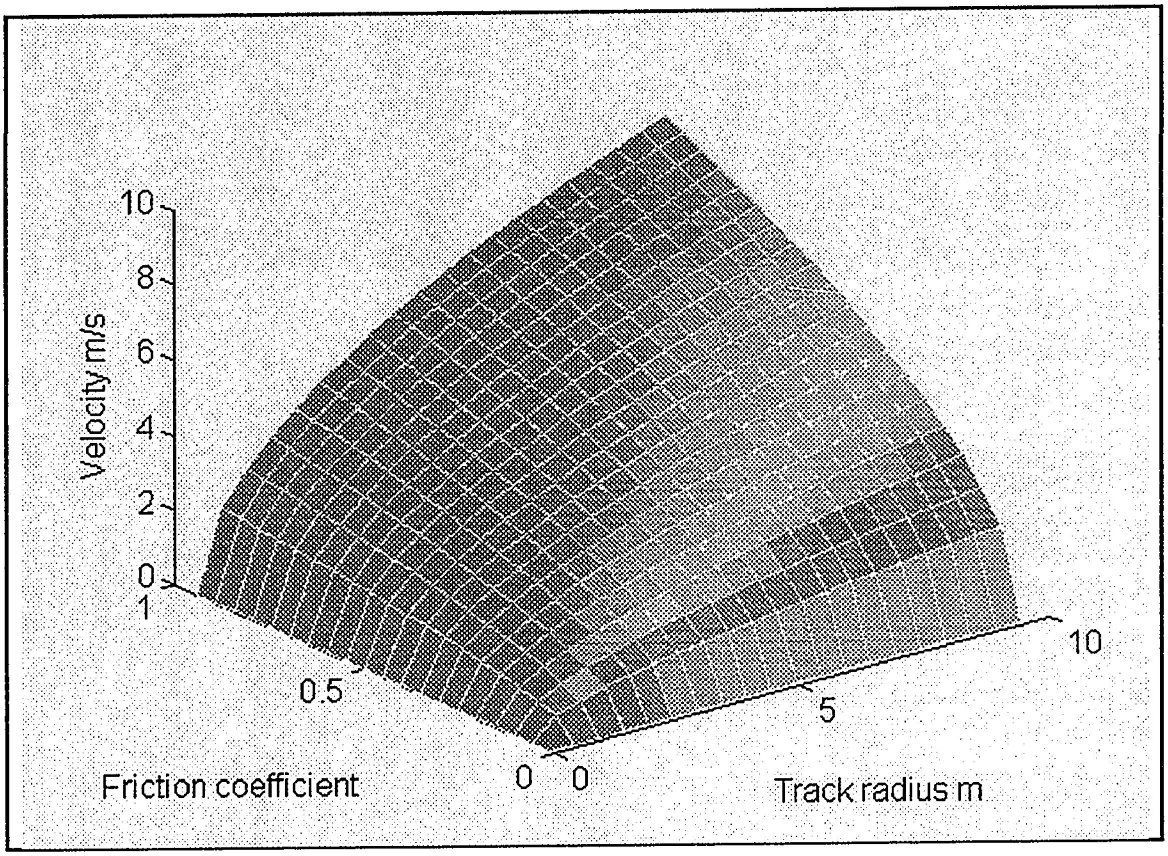

Figure 8.7 Velocity constraint for sliding and toppling when wheelbase is doubled to 2.51 m. The centre of gravity is at a height of 0.8 m.

9.0 CONCLUSIONS

9.1 Questions addressed

Current AGV technology can be used in a goods distribution centre to carry out repetitive pallet unloading and transfer without supervision. Autonomous pallet handling systems have to be carefully designed to ensure that the system does not break down under any situation. Three important questions to be answered prior to implementing autonomous control are:

- What are the feasible AGV velocities in a handling system.
- How can the AGV be guided accurately and rapidly to the pallet.
- What is the effect of AGV velocity and pallet interarrival time on the performance of the system.

The process of automated goods movement from the unloading docks to a conveyor has been modelled, and controlled AGV positioning and movement have been simulated.

9.2 Research objectives

Three research objectives have been addressed:

Objective-1

- Model intelligent material handling in a distribution centre considering the effect of dynamic constraints on the velocity profiles of an automated handling equipment (a sideload forklift AGV).

A material handling process in the distribution centre is modelled using the discrete event formalism. A discussion of modelling theory and its application to the process of carrying goods from unloading docks to conveyor is described.

A detailed discussion of the velocity profiles of an AGV is presented in chapter 4. The acceleration and maximum permitted velocity provide the constraints to be satisfied. Additionally, toppling and slipping may occur while negotiating curved paths, and provide constraints to be satisfied. Commercial AGVs typically follow 'safe' velocity profiles which may be an order of magnitude lower than the constraint limited velocities.

Objective-2

- Model and simulate controlled vision-based positioning of an AGV.

Vision based positioning of a forklift AGV is discussed in Chapter 5. A ccd camera is used as a sensor to image a retroreflecting target on a pallet. The use of a retroreflecting target greatly simplifies image processing, and a thresholding operation provides adequate information to locate the target. Image processing was done with MATLAB code written by the author. The steps followed are:

(1) Read image raw data file (obtained by using an image digitizer)

(2) Perform thresholding operation by assigning a value of "1" to all pixcel intensity levels (gray scale) greater than "55" (i.e. 55 to 64, which corresponds to the maximum intensity level for the PCEyes image digitizer used), and a value of "0" to lower intensity values.

(3) Calculate the centre of gravity of the image by taking the moment of the intensity levels and dividing by the sum of the pixcels with value "1".

Very satisfactory correlation with measured data is observed. The need for a controller arises because the AGV is to be positioned while in motion. This may give rise to error in the readings of target distance. Assuming the error is described by a normal probability distribution with a standard deviation of 1 cm, an adaptive control strategy is simulated with MATLAB code. It was found that the AGV can be satisfactorily positioned with this form of control. Model free fuzzy logic control has also been simulated. This control method is not generally superior to adaptive control, but provides a feasible alternative when an accurate model is not known.

Objective-3

- Simulate the process model and draw conclusions about the possible saving in time.

The use of SIMAN to simulate the material handling process, and the modelling steps required are discussed in chapter 7. SIMAN distinguishes between a 'model file,' where logical flow can be defined, and an 'experiment file,' which includes data accessed by the 'model file.'

Results indicate that for the system modelled, the queue of waiting jobs remains within acceptable limits for exponentially distributed interarrival times with mean greater than 15 minutes. The AGV guidepath is 104 m long and includes a staging link. It is noticed that increased AGV velocities enables the system to operate for an interarrival time of 10 minutes. The alternative strategy would be to add another AGV. This will not only increase capital cost, but also call for traffic management and enhanced communication requirements.

9.3 Feasible AGV velocities

The effect of increased torque on the service time is seen to decrease with high values of power. The return (in terms of decreased service time) resembles an asymptotic curve, and clearly indicates that a careful analysis ought to be carried out in order to justify more powerful AGVs. Since the torque-service time relation is specific to a particular network, the velocity profiles ought to be determined for any new network before conclusions can be arrived at regarding the justification for more powerful AGVs. The velocity of the AGV while going around curves is strongly dependent on the friction coefficient and the height of the centre of gravity. These factors should be accounted for when considering an AGV system.

9.4 Significance of vision-based positioning

The use of vision based AGV positioning in the distribution centre takes on particular significance in the context of the "lights out" intelligent distribution centre. The modelling framework permits the development of an "expert system" which can learn and update knowledge of system behaviour by using the results of the simulation, which reacts to changes in the parameters describing the goods reception process {Arrival rate, number of AGVs, available power, weight of load, etc.} in the manner described in "Scope for future work." The current status of research in the field of modelling and simulation of goods distribution systems does not include any research in the area of intelligent control of the process of goods unloading, integrated with a modelling framework along the lines described in the dissertation. The controller simulation, and the expert system framework discussed advances current knowledge in the field of material handling in a distribution centre. A rigorous test of whether this degree of intelligent control is an economically viable proposition is a question which remains to be answered.

9.5 Queue length variation

The feasibility of using an AGV for autonomous material handling depends on the queue length of waiting pallets which develops during operation. A high value of steady state queue length is undesirable, as is a high value of queue length in the transient phase of operation, before the system has reached steady state. The queue length as a function of time was examined by simulating the material handling process with SIMAN. The interarrival time of arriving pallets ranged from 10 minutes to 30 minutes, and the AVI from ≈3.5 m/s to ≈0.8 m/s. The AVI considered correspond to the maximum AGV velocity possible which satisfy dynamic constraints, and the velocity currently used in commercial AGVs, as discussed in chapter 4. In addition, the positioning control used also has an effect on the AVI. The results of the simulation indicate that the system does not work for low values of interarrival time when the AVI is also low. Thus, the system examined will benefit from high values of AVI. Intermediate values of AVI also demonstrate satisfactory performance, as verified from a simulation of the process with a number of AVI values and interarrival times, thus indicating that a variable AVI may prove to be the answer to the competing demands of quick transfer of pallets and safer operation and lower risk of equipment failure.

An interesting feature of simulation is the feasibility of examining the short and long term behaviour of s system. Strictly speaking, of course, a simulation can only describe transient system behaviour. For practical purposes, a simulation length in excess of ≈ 10 days is assumed to describe "steady state" system behaviour. The results of the simulation reveal that low AGV velocities result in a rapid buildup of queue length when the interarrival time is small. While the trends revealed by the simulation are predictable, it is difficult to predict the range of system parameters in which one AGV will be able to function autonomously. As revealed in **Figure 9.1,** the AGV queue increases drastically for a particular region in the Interarrival time-AVI diagram.

The previous work done in simulation of AGV systems in the context of goods handling in a distribution centre do not take into account AGV centre of gravity, wheelbase and wheel-floor friction coefficient in an explicit manner, although these factors have a profound influence on the speed at which AGV's can operate. However, the major contribution in this research is the concept of using vision based controlled positioning for material handling, and using the discrete-event modelling framework to link system performance in terms of the development of queues at the unloading docks, to AGV velocity and positioning control. The idea of using a simple, robust and practical vision system (as has been demonstrated at various similar vision system installations by Diffracto Ltd.[1]) to reduce the time needed to position the forklift, is a new concept, as is the simulation experiment with fuzzy control for vision

[1] Private communication with Diffracto Ltd., Windsor, Ontario

based positioning. Fuzzy controllers have proved their cost effectiveness in various applications ranging from process control to speed control in railway transit systems and passenger cars (The Mazda 929 passenger car, 1993). It is also model independent, and therefore very conveniently adapted to various AGV systems.

Simulation provides information regarding steady state conditions and a feasible operating region, as depicted in **Figure 9.1**. This compares very favourably with predictions of the M/D/1 queueing model for a single loop network, as can be seen from **Figure 9.2**. It is possible to obtain such "feasible operating regions" for a number of networks with multiple AGVs provided that certain constraints are satisfied (Chapter 8), thus providing information regarding the effect of AGV control on system performance.

9.6 Summary

Summarizing the conclusions, the following primary research objectives have been satisfied:
Model intelligent material handling in a distribution centre, considering the effect of dynamic constraints on the velocity profiles of an AGV.
Model and simulate controlled vision based positioning.
Simulate the process model and identify the feasible operating region.

The movement of an AGV around a track is influenced by a number of constraints. Power, friction and toppling tendency, which is a function of the centre of gravity and the wheelbase of the AGV. The torque limited AGV velocity profiles which satisfy velocity constraints are compared to currently existing AGV velocity profiles for commercial AGVs. The saving in time is found to decrease in a non linear manner as the available power increases.

A vision based positioning method, whereby the AGV approaches the pallets at a high velocity, is proposed. Controlled deceleration {Adaptive and Fuzzy} in response to inputs from the results of the simulation of AGV positioning demonstrate the applicability of the control system.

The transient behaviour of a single loop single AGV system is investigated by a simulation exercise with SIMAN. The results are extended to larger networks with multiple AGVs using queueing theory. The modelling framework opens up the possibility of expert system based intelligent control, with system performance strongly linked to motion control of automated guided vehicles.

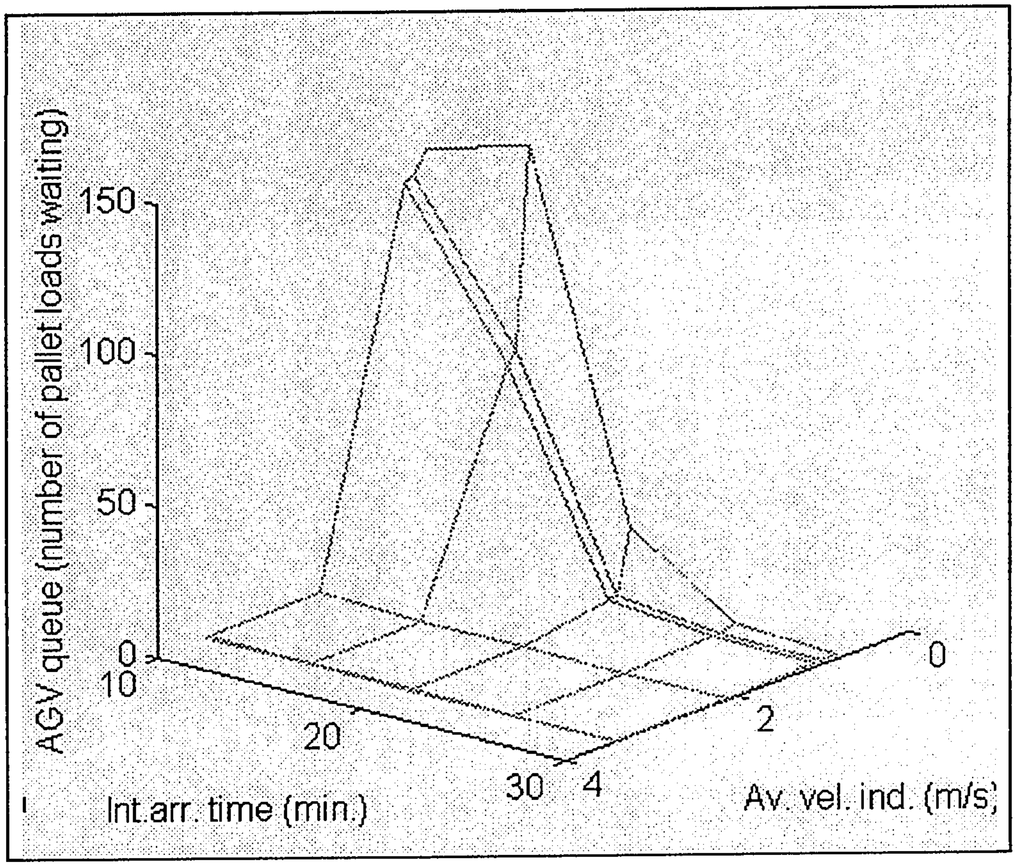

Figure 9.1 Feasible operating region for the process [P] from simulation results.

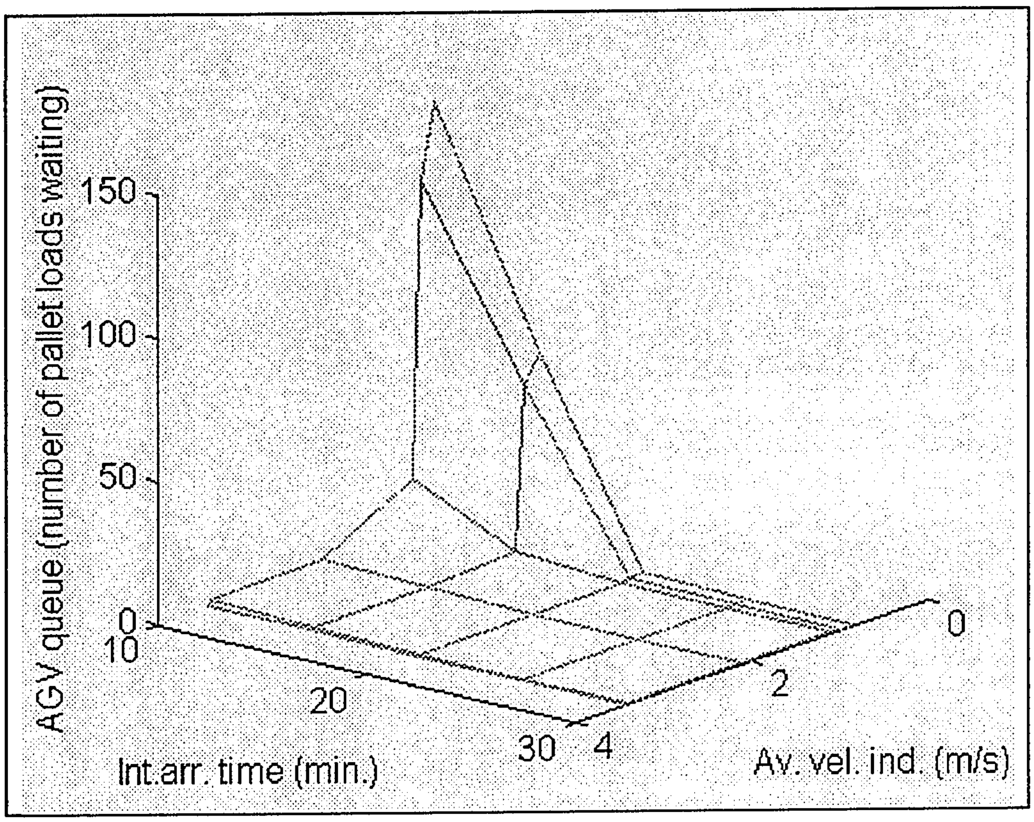

Figure 9.2 Feasible steady-state operating region for the process [P] from queueing theory.

10.0 SCOPE FOR FUTURE WORK

10.1 Intelligent Control in the Distribution Centre

Unmanned material handling equipment in a goods distribution centre may be controlled in an intelligent manner by an "expert system" as described in the flowchart **(Figure 10.1).** The "Expert System" consists of an Inference Engine, a Rule Base and sensors which supply inputs from the controlled equipment and from the unloading docks, where the interarrival time of pallet loads is monitored continuously. The rule base consists of criterion for controlling the AGV velocity. As interarrival time increases, a slower AGV velocity can be employed, thus reducing the chances of the AGV toppling over when going around curves at high velocities. The provision for multiple discrete velocities, available in commercial AGVs, can be profitably utilized by such a system.

10.2 Modelling formalism

A Discrete Event System Specification formalism can be used to design the intelligent control system, as it provides "time windows" during which the state of a system changes in response to inputs and transition rules. To give an example, an AGV will become active if there are pallets waiting at the unloading docks and this input is received by an idle AGV. The rule base supplies the appropriate outputs by using IF-THEN-ELSE rules. This formalism has been found to be well suited to controlling discrete event systems with human interaction.

The Inference Engine interfaces with the rule base and the data arriving from sensors. The output of the inference engine can be made continuous by making use of fuzzy logic. The steps to be followed in order to implement fuzzy logic in the inference engine are as follows:

- Define appropriate membership functions.

- Determine fuzzy relation matrices corresponding to various rules in the rule base (data-base).
- Generate fuzzy input from the crisp input data.
- Perform "composition" operation on the fuzzy input and the relation matrices to come up with a fuzzy output.
- Obtain a crisp output value by using a method like "centroid defuzzification."

The above mentioned steps for generating outputs using fuzzy logic and the use of the Discrete Event System Formalism in intelligent material handling have been discussed in the paper "Modelling Intelligent Materials Handling in a Goods Distribution Centre," by S Basu, V M Huynh and S P Dutta, accepted for publication in "International journal of Production Research" in 1995.

Thus, the entire process of unloading pallet loads from a truck and transferring individual pallets to an automated conveyor can be controlled intelligently.

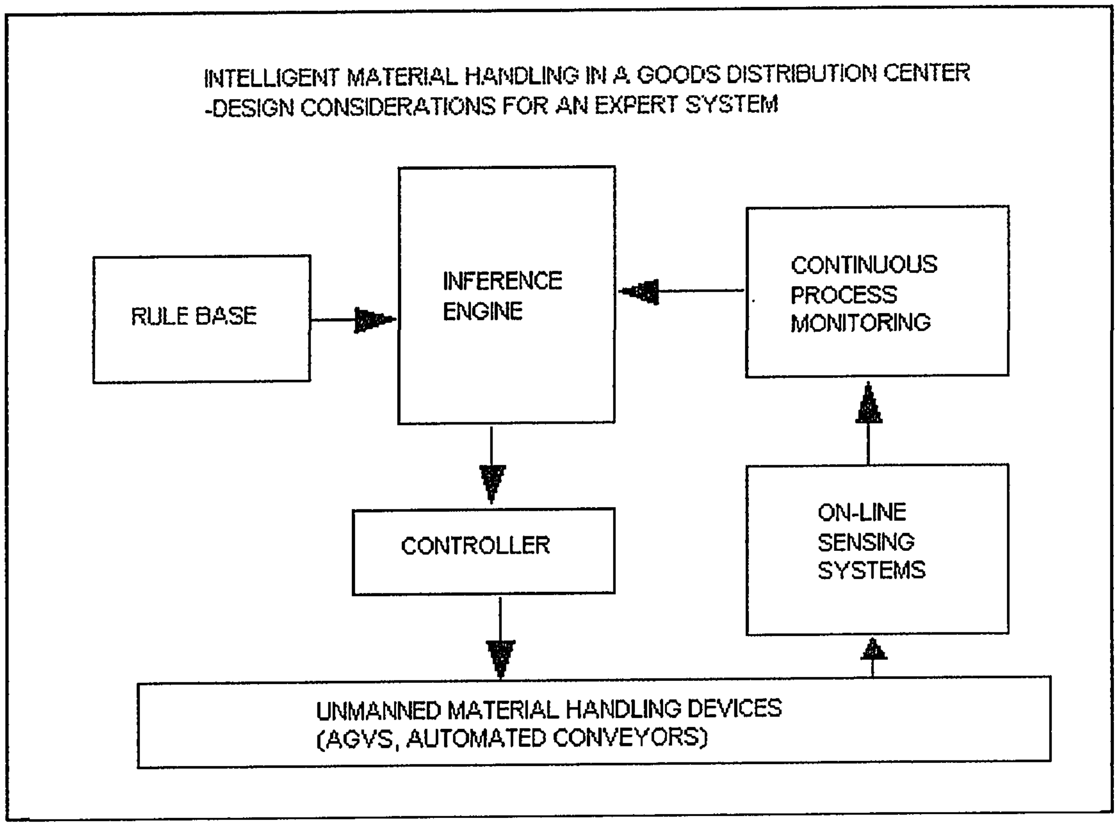

Figure 10.1 Framework for intelligent material handling in a goods distribution centre

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APPENDIX-A

{All code written by the author}

A.1 Software related to velocity profiles.

m-files were written in MATLAB in order to generate velocity profiles for various sets of initial conditions. All profiles are based on applying Newtons laws of motion to linear distance arrays. Other arrays considered are friction coefficient arrays and curve radius arrays. Height of c.g. is also considered as an array.

A.1.1 Linear velocity

m-files written in MATLB code for generating velocity profiles are listed. (General code given here will need to be modified slightly to reproduce the figures)

The particular file listed produces friction dependent velocity profiles.

```
vel-5
=================
clear;
v1      =input('v1= ');
v2      =input('v2= ');
v3      =input('v3= ');
d       =input('d= ');
%=================
mass=2633;
power=15000;
vel=4;
```

```
accln=power/(vel*mass);
s(1)    =0;
v(1)    =v1;
t(1)    =0;
for i=1:ceil(d/.01)
        s(i+1)  =s(i) + .01;
        if ( d-s(i) > (v(i)^2-v3^2)/(2*accln) )
                v(i+1)  =sqrt(v(i)^2 + 2*accln*.01);
                if v(i+1) >= v2;
                        v(i+1)=v2;
                end
                elseif ( d-s(i) <= (v(i)^2-v3^2)/(2*accln) )
                v(i+1)=sqrt(v(i)^2-(2*accln*.01));
        end
if v(i+1)==v(i)
t(i+1)=t(i)+.01/v(i+1);
elseif v(i+1)~=v(i)
t(i+1)=t(i)+abs(v(i+1)-v(i))/accln;
end
end
subplot(2,1,1);
plot(s,v);
axis([0,max(s),0,1.1*max(v)]);
grid;
text(.2,3,'Slipping')
text(.2,3,'No Slipping')
subplot(2,1,2);
plot(s,t);
axis([0,max(s),0,1.1*max(t)]);
grid;
```

d/max(t)

A.1.2 Curved path velocity surface

The m-file used to generate the feasible velocity surface for an AGV going around a curve is provided here.

curve.m

```
============
g       =9.81;  wbase  =1.257*1.5;
i       =2;             mu(1)  =0.2;
r(1)    =1;             mulast =0.9;
rlast   =10;            n      =20;
h=1.5;
delmu   =(mulast-mu(1))/n;
delr    =(rlast-r(1))/n;
        for i   =2:n
        mu(i)   =mu(i-1)+delmu;
                for j   =2:n
                r(j)    =r(j-1)+delr;
                v1(i,j) =sqrt(mu(i)*r(j)*g);              % FRICTION
                v2(i,j) =sqrt(wbase*r(j)*g/(2*h));        % TOPPLING
                end
        end
v3      =min(v1,v2);
surfl(r,mu,v3);
grid
title('
xlabel('Track radius m');
ylabel('Friction coefficient');
```

```
zlabel('Velocity m/s');
radius  =input('radius= ');
fric    =input('Mu= ');
vfric   =sqrt(fric*radius*g);              % FRICTION
vtoppl  =sqrt(wbase*radius*g/(2*h));             % TOPPLING
vmax    =min(vfric,vtoppl)
```

A.1.3 Torque surface

The m-file for generating the plot of acceleration as a function of power and velocity is provided.

```
% H.P.(metric)          = 746 Watts
% Vel (m/s)    = Km/hour * 1000/3600 = Km/hr * 0.277
% rpm (rev/s) = Assumed maximum shaft rpm
% shaftr        = Drive shaft radius
% omega (rev/s)         = v (m/s) / r (m)
% Watt                  = Torque * rev/s
pi      = 3.1415926;
grade   = 30*pi/180;
g       =9.81;
r       =0.1;           % Drivewheel radius = 0.1 m
shaftr  =0.02
v       =20 * 0.277;    % Maxvelocity (m/s from Km/hr)
mass    =3997/g                 % AGV+payload, Kg
omega   =v/r;
i       =1;
j       =1;
for hp=45:50
        for vel=10:20
                w(i)    =hp * 746;
                om(j)   =vel/r;
                t(i,j)  =w(i)/om(j)
                i       =i+1;
        end
        j       =j+1;
end
```

```
w1      =w/746;
%mesh(w,om,t);
%grid;
hpp     =input('Horsepower= ')
%rpm  =input('Maxm. rev/min= ')
i=1;
j=2;
hp(1)   =hpp;
for m=hpp:5*hpp:hpp*.1
        for n=0:15
                nn      =sqrt(2)^n
                rps     =nn*v/r;
                torq(i,j)       =m*746/rps;
                accln1(i,j)     =torq(i)/(r*mass);
                i=i+1;
                j=j+1;
        end
end
accln2 =g*(sin(grade));
plot(accln1,'g*');
hold;
plot(accln1,'r-');
hold;
```

A.1.4 Image center of gravity

The code used to calculate the centre of gravity of the image retrieved from a ccd camera is given here. It is not a 'stand alone' code, and companion code to read the image file and generate the "cc" array (rectangular; n1 x n2) is required to produce the final result.

```
cgx=0;              cgy=0;
mmtx1(1)=0;  mmtx2(1)=0;
sx1(1)=0;       sx2(1)=0;
for i=1:n1
             mmtx1(i,1)=0;          mmtx2(i,1)=0;
             for j=1:n2
                          mmtx1(i,j+1)=         mmtx1(i,j)+cc(i,j);
                          mmtx2(i,j+1)=         mmtx2(i,j)+cc(i,j)*j;
             end
             sx1(i+1)=      sx1(i)+mmtx1(i,n2+1);
             sx2(i+1)=      sx2(i)+mmtx2(i,n2+1);
end
cgx=2*sx2(n1+1)/sx1(n2+1)

mmty2(1)=0;  sy2(1)=0;
for j=1:n2
             mmty2(1,j)=0;
             for i=1:n1
                          mmty2(i+1,j)=         mmty2(i,j)+cc(i,j)*i;
             end
             sy2(j+1)=      sy2(j)+mmty2(n1+1,j);
end
cgy=2*sy2(n2+1)/sx1(n2+1)
xoffsey=0;yoffset=0;
xoffset=cgx-n1/2
yoffset=cgy-n2/2
```

A.1.5 Fuzzy positioning

The m-file required for fuzzy positioning control with three membership functions is provided here. Depending on the particular requirements, it may be modified to produce desired outputs.

```
dt      =0.1;           v(1)   =2.49;
% v(1)=Curve velocity
s(1)    =2.0;           ac(1)  =v(1)^2/(2*s(1));     % s(1)=posn.distance
%_________________________________
error(1)=0;
i       =2;             var    =10;
ii      =0;             varr   =10;
while (abs(varr)>0.1)
        v(i)    =v(i-1)-ac(i-1)*dt;
        var     =v(i-1)*dt-0.5*ac(i-1)*dt^2;
        error(i)=randn/10;
        s(i)    =s(i-1)-var+error(i);
        if s(i)>s(i-1)
                s(i)=s(i-1);
        end
        varr    =s(i);
        %----------------Fuzzy Controller----------------%
        ii=error(i)*10;
        n=1;
        %=========Membership function vertices========
        x(1,1)=-5;      x(1,2)=-3;      x(1,3)=-2;      x(1,4)=0;
        x(2,1)=-2;      x(2,2)=0;       x(2,3)=0;       x(2,4)=2;
        x(3,1)=0;       x(3,2)=2;       x(3,3)=3;       x(3,4)=5;
        step=0.5;
```

```
%=========Input fuzzy set vertices============
in(1)=ii-1;     in(2)=ii-0.2;
in(3)=ii+0.2;   in(4)=ii+1;
%=============================================
% FIRST MEMBERSHIP
for j=-5:step:5
        if j<x(1,2)
                a(n)=(j-x(1,1))/(x(1,2)-x(1,1));
                axisa(n)=j;
                elseif (j<x(1,3) & j>=x(1,2))
                a(n)=1;
                axisa(n)=j;
                elseif (j<=x(1,4) & i>=x(1,3))
                a(n)=1-((j-x(1,3))/(x(1,4)-x(1,3)));
                axisa(n)=j;
                elseif (j>x(1,4))
                a(n)=0;
                axisa(n)=j;
        end
        n=n+1;
        %plot(axisa,a)
end
%hold
n=1;
% SECOND MEMBERSHIP
for j=-5:step:5
        if j<x(2,1)
                b(n)=0;
                axisb(n)=j;
                elseif (j>=x(2,1) & i<x(2,2))
```

```
                b(n)=(j-x(2,1))/(x(2,2)-x(2,1));
                axisb(n)=j;
                elseif (j<x(2,3) & j>=x(2,2))
                b(n)=1;
                axisb(n)=j;
                elseif (j<=x(2,4) & j>=x(2,3))
                b(n)=1-((j-x(2,3))/(x(2,4)-x(2,3)));
                axisb(n)=j;
                elseif (j>x(2,4))
                b(n)=0;
                axisb(n)=j;
        end
        n=n+1;
        %plot(axisb,b)
end
n=1;
% THIRD MEMBERSHIP
for j=-5:step:5
        if j<x(3,1)
                c(n)=0;
                axisc(n)=j;
                elseif (j>=x(3,1) & i<x(3,2))
                c(n)=(j-x(3,1))/(x(3,2)-x(3,1));
                axisc(n)=j;
                elseif (j<x(3,3) & j>=x(3,2))
                c(n)=1;
                axisc(n)=j;
                elseif (j<=x(3,4) & j>=x(3,3))
                c(n)=1-((j-x(3,3))/(x(3,4)-x(3,3)));
                axisc(n)=j;
```

```
                elseif (j>x(3,4))
                c(n)=0;
                axisc(n)=j;
        end
        n=n+1;
        %plot(axisc,c)
end
n=1;
% INPUT MEMBERSHIP
for j=-5:step:5
        if j<in(1)
                d(n)=0;
                axisi(n)=j;
                elseif (j>=in(1) & j<in(2))
                d(n)=(j-in(1))/(in(2)-in(1));
                axisi(n)=j;
                elseif (j<in(3) & j>=in(2))
                d(n)=1;
                axisi(n)=j;
                elseif (j<=in(4) & j>=in(3))
                d(n)=1-((j-in(3))/(in(4)-in(3)));
                axisi(n)=j;
                elseif (j>in(4))
                d(n)=0;
                axisi(n)=j;
        end
        plot(axisi,d,'y-')
        n=n+1;
end
%=========================================
```

```
% RULES:   IF HIGH THEN LOW
%          IF MEDIUM THEN MEDIUM
%          IF LOW THEN HIGH
%     RELATION BETWEEN 1&3, 2&2, AND 3&2
%     ARE NEEDED.
%========================================
var=i;
% RELATION MATRIX..RULE-1{IF HIGH THEN LOW}
for i=1:n-1,
        for j=1:n-1,
                r1(j,i)=min(a(i),c(j));
        end
end

% RELATION MATRIX..RULE-2{IF MEDIUM THEN MEDIUM}
for i=1:n-1,
        for j=1:n-1,
                r2(j,i)=min(b(i),b(j));
        end
end

% RELATION MATRIX..RULE-3{IF LOW THEN HIGH}
for i=1:n-1,
        for j=1:n-1,
                r3(j,i)=min(c(i),a(j));
        end
end

% COMPOSITION..1
for i=1:n-1,
```

```
big1=0;
        for j=1:n-1,
                temp1(j,i)=min(d(j),r1(j,i));
                big1=max(big1,temp1(j,i));
        end
comp1(i)=big1;
end

% COMPOSITION..2
for i=1:n-1,
big2=0;
        for j=1:n-1,
                temp2(j,i)=min(d(j),r2(j,i));
                big2=max(big2,temp2(j,i));
        end
comp2(i)=big2;
end

% COMPOSITION..3
for i=1:n-1,
big3=0;
        for j=1:n-1,
                temp3(j,i)=min(d(j),r3(j,i));
                big3=max(big3,temp3(j,i));
        end
comp3(i)=big3;
end

% Find centroid
outset=max(comp1,comp2); outset=max(outset,comp3);
```

```
sumarea=0; summoment=0; moment=0;n=1;centre=0;
for j=(-5+step/2):step:(5-step/2),
        area(n)=0.5*(outset(n)+outset(n+1))*step;
        sumarea=sumarea+area(n);
        mt(n)=(j+(step/2))*area(n);
        summoment=summoment+mt(n);
        area(n);
%       x(n)=j;
n=n+1;
end
if sumarea>0
        centre=summoment/sumarea;
        elseif sumarea==0;
        centre=0;
end
i=var;
ac(i)=centre/2;
%-----------------------------------------------%
i=i+1;
end
```

A.1.6 Discussion of fuzzy control

The fuzzy controller accepts an input fuzzy set, created by fuzzifying a crisp input value. The vertices of the input trapezoid fuzzy set are calculated by offsetting the crisp input by 0.2 and 0.1 cm, which implies that we are not certain about the input variable (say "x") in the range x±1 to x±0.2 cm. Relation matrices corresponding to various fuzzy rules are computed by performing a minimization operation on the membership functions comprising the rule.

The output of the fuzzy controller is calculated by performing a minimization operation on the input and relation (rule) arrays, and extracting the maximum element corresponding to each column of the composition array. Thus we get a vector corresponding to each fuzzy composition operation. The maximum elements of all such vecors provide the output fuzzy polygon. By calculating the centroid of the polygon, the crisp output value can be found.

Table A-1 Technical specifications of F-30/40 sideload forklift AGV from BT Systems Inc.

Overall dimensions, weight and speed:

Length	:2.54 m
Width	:1.76 m
Height	:2.23 m
Payload	:1364.00 Kg
Mass of AGV	:2633.00 Kg
Max. drive speed	:1.00 m/s
Max. manual speed	:0.75 m/s
Medium drive speed	:0.50 m/s
Low drive speed	:0.20 m/s
Creep speed	:0.10 m/s

Table A-2 Time (s) to go across links as a function of AGV torque for network in Figure 3.2

When the AGV travels across the links of the network depicted in Figure 3.2, the time of travel is computed based on the assumption of a maximum velocity of 10 m/s and available torque. Neglecting time for moving forks at the loading and unloading stations, and the time needed to travel across the staging links, the time needed to cross various links varies as shown in the following table.

Link #	Torque (N.m)				
	375	750	1125	1500	1875
1	1.6759	1.1943	0.9971	0.8811	0.8026
2	1.4527	1.4414	1.44	1.4376	1.4375
3	5.1978	4.2005	3.6585	3.3683	3.1951
4	1.5974	1.5974	1.5974	1.5974	1.5974
5	5.9256	4.4345	3.7665	3.3439	3.1136
6	6.0871	4.5495	3.8179	3.3901	3.1319
7	1.5974	1.5974	1.5974	1.5974	1.5974
8	2.1514	1.8649	1.6797	1.5457	1.4459
9	1.4337	1.4337	1.4337	1.4337	1.4337
10	1.278	1.278	1.278	1.278	1.278
11	1.278	1.278	1.278	1.278	1.278

Appendix-B

Fork travel time

The commercially available AGV whose specifications are provided in table B-1 needs a certain amount of time to move the forks. This is calculated as shown:

Speed of fork movement (in vertical and horizontal directions) = 0.2 m/s.

Horizontal travel time = distance / velocity = 1.2 m / 0.2 m/s = 6 s.

Vertical travel time = distance / velocity = 0.5 m / 0.2 m/s = 2.5 s.

Total time needed to reach-raise-withdraw = 14.5 s = 15 s approx.

Appendix-C

C-1 Modified network (Figure 8.24) dock travel time

The following m-file calculated dock travel time, and can be adapted to calculate the time needed to travel to either of docks 1,2 and 3.

```
clear;
mass        =2633;       pwr         =15000;
vel         =4;          accln       =pwr/(vel*mass);
vcurve1     =2.83;       vcurve2     =3.13
tt          =0;
%___________loading / Unloading_______________
load        =1.2 + 6;
unload      =6;
% AGV accelerates from rest to vcurve1 over link d1
% AGV accelerates from max(v) at end of d1 to vcurve1 over link d2
%_____________Link 1______________________
vv(1,1)     =0;          vv(1,2)     =10;
vv(1,3)     =vcurve1;    dd          =8;
try1
title ('Link 1')
tt          =tt+t(i)
pause
%_____________Link d0______________________
vv(1,1)     =vcurve1;         vv(1,2)     =vcurve1;
vv(1,3)     =vcurve1;    dd          =4;
try1
title ('Link 0')
```

```
tt              =tt+t(i)
pause
%______________Controlled positioning____________
tt              =tt+load;
%______________Link d1______________________
vv(1,1)         =0;           vv(1,2)         =10;
vv(1,3)         =vcurve1;     dd              =2;
try1
title ('Link d1')
tt              =tt+t(i)
pause
%______________Link d2______________________
vv(1,1)         =v(i);        vv(1,2)         =10;
vv(1,3)         =vcurve1;     dd              =2;
try1
title ('Link d2')
tt              =tt+t(i)
pause
%______________Link #2 _____________________
vv(1,1)         =v(i);        vv(1,2)         =10;
vv(1,3)         =vcurve2;     dd              =(6.55*2)+8;
try1
title ('Link 2')
tt              =tt+t(i)
pause
%______________Link #3 _____________________
vv(1,1)         =v(i);        vv(1,2)         =10;
vv(1,3)         =vcurve2;     dd              =(6.55*2)+8;
try1
title ('Link 3')
```

```
tt              =tt+t(i)
pause
%______________Link #4 _____________________
vv(1,1)         =v(i);          vv(1,2)         =10;
vv(1,3)         =0;             dd              =17.83;
try1
title ('Link 4')
tt              =tt+t(i)
pause
%______________Link #5 _____________________
vv(1,1)         =v(i);          vv(1,2)         =10;
vv(1,3)         =vcurve2;       dd              =17.83;
try1
title ('Link 5')
tt              =tt+t(i)
pause
%______________Link #6 _____________________
vv(1,1)         =v(i);          vv(1,2)         =vcurve2;
vv(1,3)         =vcurve2;       dd              =5;
try1
title ('Link 6')
tt              =tt+t(i)
pause
lasttime=t(i)
```

```
clear;
v1      =input('v1= ');
v2      =input('v2= ');
v3      =input('v3= ');
d       =input('d= ');
%================
vel     =4;
mass    =2633+1364;
pwr     =15000;
accln   =pwr/(vel*mass);
s(1)    =0;
v(1)    =v1;
t(1)    =0;
for i=1:ceil(d/.01)
        s(i+1)  =s(i) + .01;
        if ( d-s(i) > (v(i)^2-v3^2)/(2*accln) )
                v(i+1)  =sqrt(v(i)^2 + 2*accln*.01);
                if v(i+1) >= v2;
                        v(i+1)=v2;
                end
                elseif ( d-s(i) <= (v(i)^2-v3^2)/(2*accln) )
                v(i+1)=sqrt(v(i)^2-(2*accln*.01));
        end
if v(i+1)==v(i)
t(i+1)=t(i)+.01/v(i+1);
elseif v(i+1)~=v(i)
t(i+1)=t(i)+abs(v(i+1)-v(i))/accln;
end
end
subplot(2,1,1);
```

```
plot(s,v);
axis([0,max(s),0,1.1*max(v)]);
grid;
%text(.2,3,'Slipping')
%text(.2,3,'No Slipping')
subplot(2,1,2);
plot(s,t);
axis([0,max(s),0,1.1*max(t)]);
grid;
max(t)
d/max(t)
```

Appendix-D

Commands used to create Model file in SIMAN

(a) BEGIN;

The generation of an output to the screen is controlled by this particular statement. The command has several other options, which are not used in this particular simulation.

(b) CREATE: EXPONENTIAL(900,1):

Entities are created with the CREATE command. The number of batches (Here, batchsize=1)

can be specified, so that the number of entities created at every trigger can be controlled. The interarrival time between consecutive arrivals may be specified as a discrete or continuous probability distribution. In this case, an exponential probability distribution is used.

(c) MARK(TIMEIN);

This command marks the time when tally variables are to be collected. Thus, the time between the MARK command and the tally command may be measured and output.

(d) ASSIGN: M=ENTER;

This variable specifies the station at which the entity is located. Once assigned, the successive states of the entity are determined by SIMAN.

(e) QUEUE, agvq;

Entities queue up to be serviced by an AGV. This is very often a necessary part of the modelling process. In most situations, this queue length is to be minimized.

(f) REQUEST: AGV(SDS);

This REQUEST command causes the nearest AGV to proceed to the entity. If the AGV is busy, the command does not achieve its goal immediately, and is executed when the preceding entities have been serviced.

(g) DELAY:

The time taken for certain activities can be modelled as a fixed delay. That is when this command is generally used.

(h) TRANSPORT:

The movement of an entity with an AGV is modelled in SIMAN with the TRANSPORT command. The location of the entity is updated and a delay equal to the time required for the move (calculated by SIMAN) is added.

(i) STATION,

This command defines a physical / logical location which is referenced by SIMAN.

(j) TALLY:

Statistics on time elapsed, etc. are collected by using the TALLY command. The location of the command in the model file often determines the magnitude of the variable measured.

(k) BRANCH

Transfer of entities to various points, or jumping to various logic flow paths can be accomplished with the conditional BRANCH command.

(l) FREE:

The FREE command releases an AGV from an entity. Successive locations of both have to be explicitly specified.

The model of the process is distinguished from the experiment frame in SIMAN. The two files are compiled separately and linked to generate a complete description of the process suitable for simulation. The compiled and linked program is termed the project file, and may be run as a simulation model to generate statistical data requested in the experiment file.

In general, the model file contains a logical description of events. This corresponds to the process of abstraction in the modelling process. The graphical model-building environment of SIMAN provides a convenient method of converting a process description into SIMAN code. The SIMAN model of the process described in **Figure 6.1** is presented in **Figure 6.2.**

The experiment file contains data and requests for statistical information, which are referenced by the model file. In order to simulate the process described, The inputs needed to simulate the process consist of:

1. Arrival pattern of pallet loads of goods carried in trailer trucks (ENTITY INTERARRIVAL TIME).
2. Number of pallets (ENTITY BATCH SIZE) of arriving trailer truck.
3. The time taken for loading/unloading.
4. The velocity of the AGV while
    a) Moving along straight links in the AGV guidepath.
    b) Moving along curves.
    c) Positioning the forks.
5. The physical layout of the AGV guidepaths with complete dimensions, to be used by the simulation package in calculating time of travel, etc.
6. The dimensions of the AGV, the speeds at which it is capable of travelling, and the minimum turn radius.

APPENDIX-B

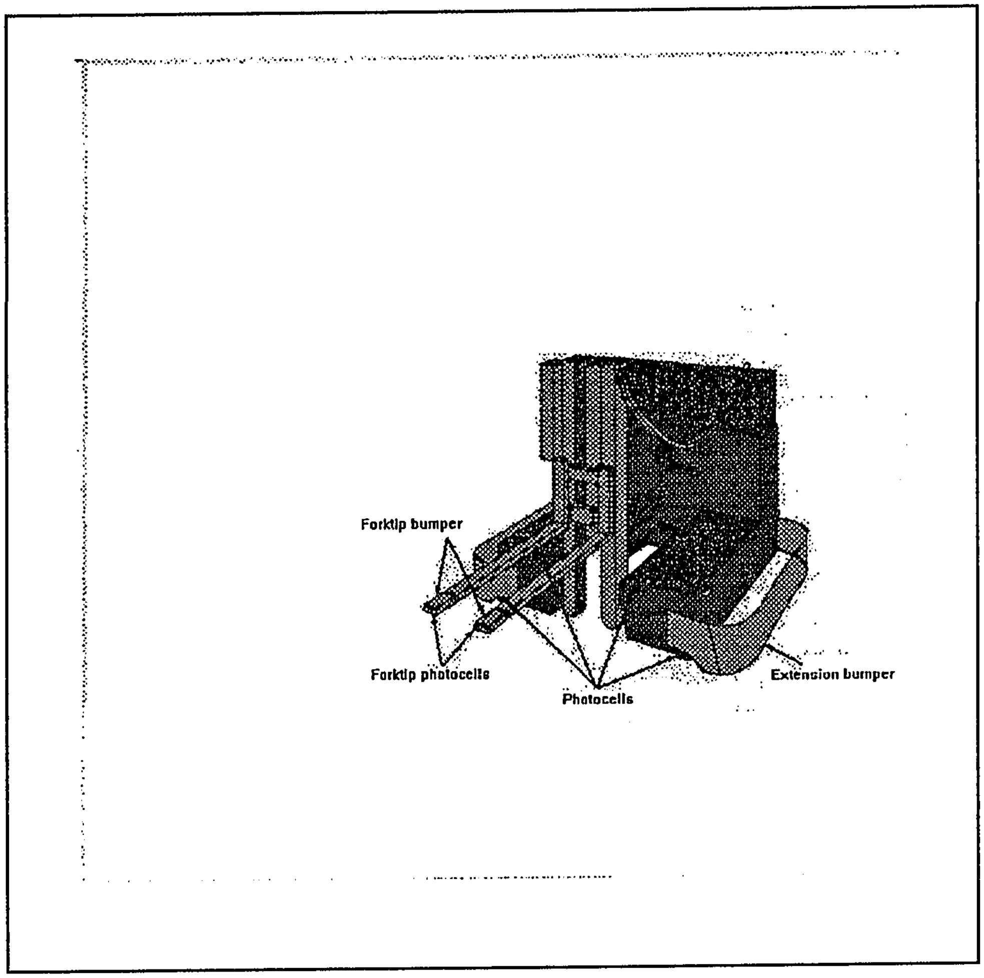

Figure B-1 Image of commercial sideload forklift AGV
(F-30/40 sideload forklift AGV from
BT Systems Inc.,7000 Nineteen Mile Rd.,
Stirling Heights, MI 48078)

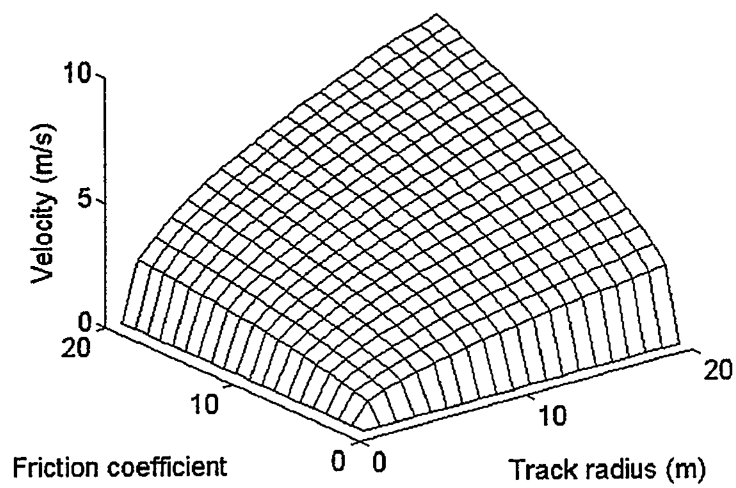

Figure B-2 Friction limited velocity of an AGV going around a curve

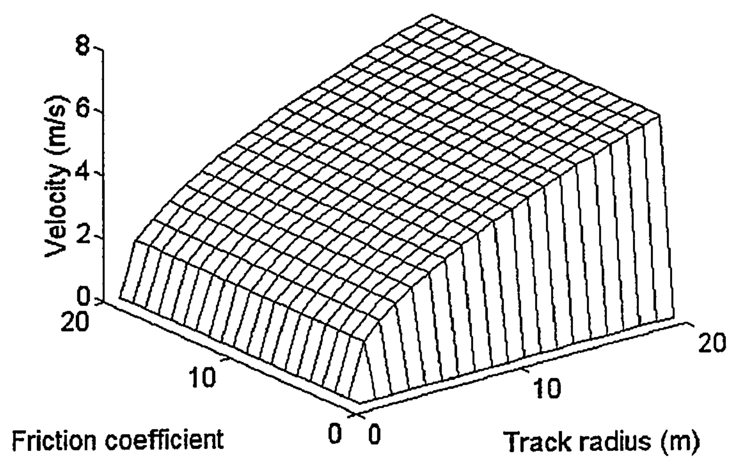

Figure B-3 Toppling limited velocity of an AGV going around a curve

TABLE B-1 Technical specifications of F-30/40 sideload forklift AGV from BT Systems Inc.

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Height:	2.23 m
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Weight of AGV:	2633.00 Kg
Max. drive speed:	1.00 m/s
Max. manual speed:	0.75 m/s
Medium drive speed:	0.50 m/s
Low drive speed:	0.20 m/s
Creep speed:	0.10 m/s

VITA ACTUORIS

1961 Born in Calcutta, India

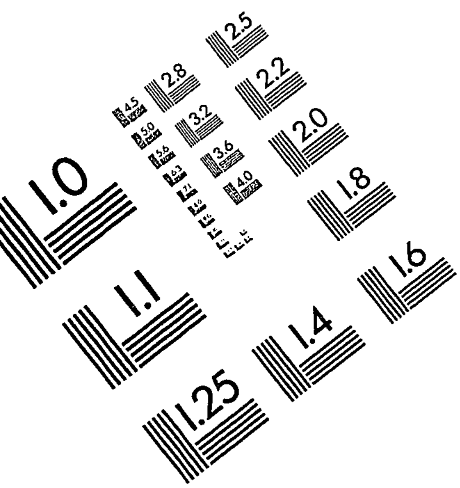
1984 Received Bsc Engg in Production Engineering from BIT Mesra, Ranchi, India

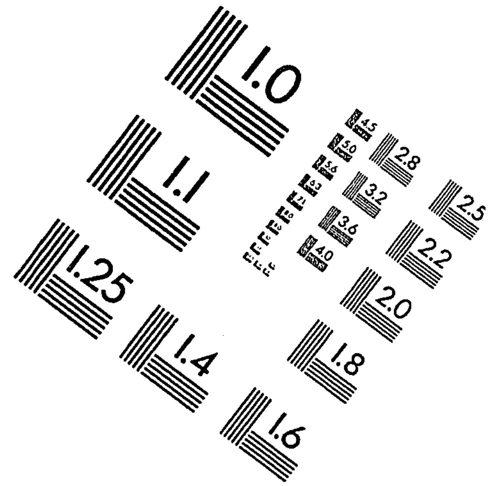
1986 Received ME in Production Engineering from Jadavpur University, Calcutta, India

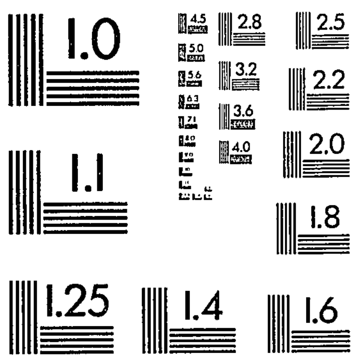
1992 Received MS in Materials Science and Engineering from Penn State University, State College, PA, USA

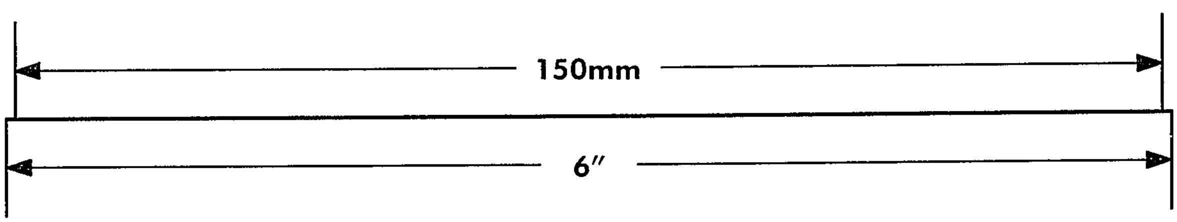
1996 Currently a PhD candidate in Mechanical and Materials Engineering at the University of Windsor, Windsor, Ontario

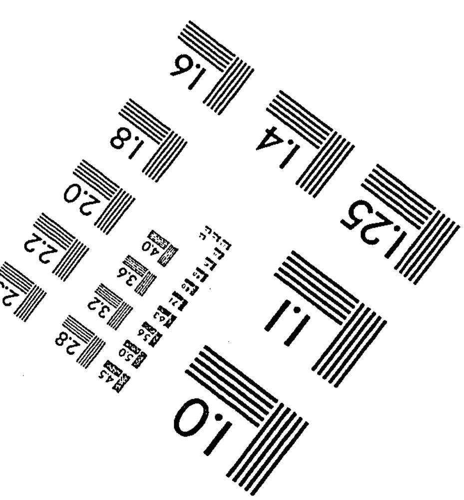
IMAGE EVALUATION TEST TARGET (QA-3)

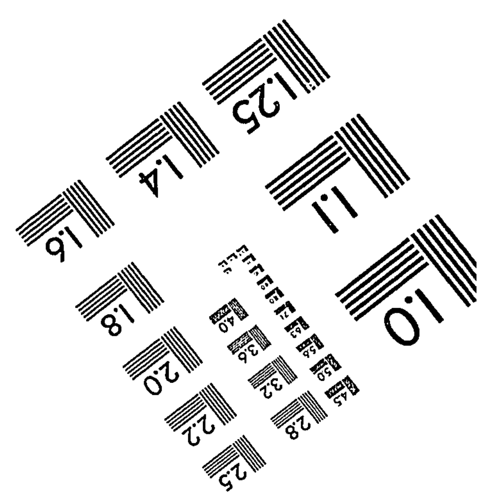












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